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TRAJECTORY ANALYSIS OF WINTER STORMS IN THE MUSKOKA REGION, 1978-79 and 1980-81

Report No 84-191-K

J.E. Grabenstetter
Research Chemist
Atmospheric Research Section
Chemical Research Department

ABSTRACT

A number of techniques were applied to study the origins of the ionic load in the Muskoka snowpack in 1978-79 and 1980-81. Major snowstorms were identified and classified as to direction of air parcel origin on the basis of calculated air parcel trajectories. For 1980-81 the correlations between direction of air parcel origin and chemical variables, as well as correlations between pairs of chemical variables, were examined. For 1978-79 no satisfactory event chemical data are available. The 1980-81 data show nitric acid to be the main acidifier and show polluted events to arise principally from the south. The more severe spring runoff of 1978-79 appears to originate from the melt timing rather than from chemical effects.

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To Mr. F.J. Kee
Director of Research

TRAJECTORY ANALYSIS OF WINTER STORMS IN THE MUSKOKA REGION, 1978-79 and 1980-81

1.0 INTRODUCTION AND OBJECTIVES

Severe episodes of acidic precipitation can lower the pH values of streams in remote areas of Ontario at virtually any time of year (Kurtz et al, 1984). Such pH depressions are of particular biological importance during spring because of the potential effects upon fish eggs in the streams (Jeffries et al, 1979).

A factor contributing to the spring pH depression is the sudden release during melting of atmospherically transported pollutants stored in the snowpack. However, the maximal pH depression usually occurs somewhat after the snowpack has completely melted, which suggests that heavy spring rains draining quickly to streams may contribute significantly to the pH depression.

Nonetheless, melt runoff undoubtedly contributes importantly to the spring pH depression in streams in remote areas of Ontario. It is therefore of interest to examine the principal snow episodes during particular winters to determine whether there is a correlation between pollutant transport processes, as judged from winter storm air parcel trajectories, and the ionic content of the snow deposited during the storm. Further, it is of interest to examine whether correlations can be established between storm meteorology and either snowpack chemistry or the magnitude of the springtime pH depression in streams.

The objectives of this study can be briefly stated as follows:

(i) Examine major winter storms in a remote region of Ontario and determine correlations between air parcel trajectories and ionic content of precipitation.

(ii) Examine the relationship between precipitation chemistry and stream chemistry.

(iii) Arrive at a preliminary understanding of the factors determining severe spring pH depressions in streams by comparing two different winters

In the sections which follow, the selection of two winters for study is described. The available chemical data are surveyed, and the method by which the air parcel trajectories are determined is described. Finally, the correlations between variables are examined and discussed.

2.0 REVIEW OF PREVIOUS WORK

In this section relevant published studies are identified and the data and findings presented in them are reviewed. The studies cited here deal directly with the relationship between atmospheric deposition and natural waters in the Muskoka region. No attempt is made to review the entire field of air parcel trajectory or snowpack studies. In the two subsections which follow, six particularly relevant studies are summarized.

2.1 Data Presented

1. Jeffries and Snyder (1981):
   (a) Major-ion analyses of snow cores and bulk deposition collected in Muskoka in 1976-77, 1977-78, 1978-79, and 1980-81.
   (b) Snowpack vertical profiles of $[H^+]$ and $[SO_4^=]+[NO_3^-]$, 1981, Muskoka.
   (c) Muskoka stream pH depressions, spring 1979.
   (d) $[SO_4^=]/[NO_3^-]$ in Muskoka lake inlet streams before, during, and after 1979 spring melt.

2. Jeffries, Cox, and Dillon (1979):
   (a) Detailed geological descriptions of several Muskoka streams.
   (b) Precipitation, discharge, and $[H^+]$ load rates for several Muskoka streams as time series.
   (c) Calculated percentage of H^+ retained in watershed.

3. Scheider, Jeffries, and Dillon (1979):
   (a) Volume-weighted precipitation average $[H^+]$, both bulk and wet-only, August, 1976-October, 1978, for several locations both on and off the Canadian shield.
   (b) Titration curves for lakes of varying degrees of acidification.
   (c) Time series of $[H^+]$ in two Muskoka streams during a summer 1977 event.
   (d) pH and alkalinity values for a selection of Muskoka lakes.
   (c) Spring pH depressions of inlet streams to several Muskoka lakes, 1976 and 1977.

4. Dillon, Jeffries, and Scheider (1982):

   (a) Mass balances of Cl^-, Ca^{+2}, phosphorus, and acids in Harp Lake, Muskoka, 1977-78.

   (b) Sulfate balances for several watersheds near Sudbury.

5. Kurtz and Scheider (1982):

   (a) Precipitation events on composite periods classified by octant of wind origin as judged by air parcel trajectories for summer and winter events in Muskoka, 1976-79.

   (b) Maximal loadings of major ions, by octant, classified as winter and summer events.

   (c) Weighted average concentrations of H^+, $SO_4^=$, and NO_3^-, classified by octant of origin and season.

6. Kurtz et al (1984):

   (a) Daily average precipitation $[H^+]$, $[SO_4^=]$, and $[NO_3^-]$ at Muskoka during an extended episode of acidic precipitation, August-September, 1981.

   (b) Total deposition fluxes and ambient aerosol concentrations, same period.

   (c) Backward air-parcel trajectories from Muskoka, several altitudes.

   (d) Correlation of precipitation ionic concentrations with octant of air parcel origin.

2.2 Findings

The major findings of these six studies are summarized as follows. The numbers after the description refer to the ordering, in the preceding subsection.

(a) Muskoka streams undergo a depression of pH values below annual averages during spring runoff and after heavy storms. In spring the peak stream $[H^+]$ coincides with peak flow; the maximal $[H^+]$ is typically 2 to 3 times the annual average (1,2,3).

(b) Stream ionic compositions differ significantly from bulk precipitation compositions, principally because of retention of H^+ in watersheds from neutralization by rocks and because of uptake of NH_4^+ and NO_3^- by biological activity. H_2SO_4 is the major springtime stream acidifier despite the deposition in precipitation of equal or greater loads of NO_3^- during the winter. Only a small fraction (<1%-20%, depending on watershed characteristics) of atmospherically deposited H^+ reaches the streams. In Muskoka, in contrast to Norway, the first fraction of spring runoff appears not to carry a disproportionately heavy ionic load (1-4).

(c) Ionic concentrations in snow cores, which represent a vertical average through the snowpack, are significantly lower than in the corresponding bulk deposition. Ionic concentrations decrease with depth in the snowpack, with the ground acting as a sink even in periods without significant thawing (1).

(d) The geological characteristics of the watershed are the major determiners of annual average stream pH, through determination of drainage times and neutralization processes. The precambrian rock of the Canadian shield is a poor neutralizer, both on the surface and as an aerosol. The neutralization weathering of rock is due mainly to airborne pollutants and only slightly to atmospheric CO_2 (2,3,4).

(e) A large fraction of the annual stream H^+ load is discharged during spring runoff. Disproportionately large fractions of the annual H^+ load in precipitation are associated with intense precipitation episodes in spring and fall (2,6).

(f) Occurrence of precipitation events and total ionic loading in precipitation are associated mainly with air parcel trajectories originating in the south and southwest octants. The situation for ionic concentrations is unclear because of the rarity of precipitation events from some octants, but high concentrations do appear correlated with trajectories from the south, southwest, and west (5,6).

3.0 SELECTION OF EVENTS AND DATA

In this section the criteria used to select winters for study and to select events from each winter are discussed and the available meteorological and chemical data are surveyed.

3.1 Selection of Winters

This study was conceived as a comparison of two winters, one preceding a severe spring pH shock and one a mild pH shock. Personnel of the Ontario Ministry of the Environment (OME) Water Resources Branch suggested the winter of 1978-79 as that preceding a severe shock and winter 1980-81 as that preceding a mild one on the basis of subjective considerations of fish populations in those years (T. Brydges, Ontario Ministry of the Environment, private communication).

Measured stream pH values do not show a corresponding pattern in the magnitudes of the spring pH depressions. Magnitudes derived from time series of stream pH measurements in three lake inlets in the Muskoka region are displayed in Table 1; the time series are shown graphically in Figures 1-3 (W. Scheider, Ontario Ministry of the Environment, private communication). Greater depressions in pH, and greater increases in $[H^+]$, occurred in 1981 than in 1979 in two of the three streams listed. No general conclusion can be drawn from this because the sample is extremely small; it was chosen to coincide with the set of streams studied intensively by OME

Table 1. Spring pH and [Ht] depressions in inlet streams of lakes in Muskoka, 1979 and 1981.

Stream	1979				1981			
	pH				pH			
	Ave	Min	Diff	Date (min)	Ave	Min	Diff	Date (min)
Harp Lake #4	6.3	5.4	0.9	Apr. 3	6.5	5.8	0.7	Feb. 24
Paint Lake #1	5.4	5.0	0.4	Apr. 3	5.6	5.0	0.6	Feb. 23
Dickie Lake #10	4.7	4.5	0.2	Mar. 20	4.9	4.5	0.4	Mar. 12
	$[H^+]$				$[H^+]$			
Harp Lake #4	$6x10^{-7}$	$4x10^{-6}$	$3x10^{-6}$		$3x10^{-7}$	$2x10^{-6}$	$2x10^{-6}$	
Paint Lake #1	$4x10^{-6}$	$1x10^{-5}$	$6x10^{-6}$		$3x10^{-6}$	$1x10^{-5}$	$7x10^{-6}$	
Dickie Lake #10	$2x10^{-5}$	$3x10^{-5}$	$1x10^{-5}$		$1x10^{-5}$	$3x10^{-5}$	$2x10^{-5}$	

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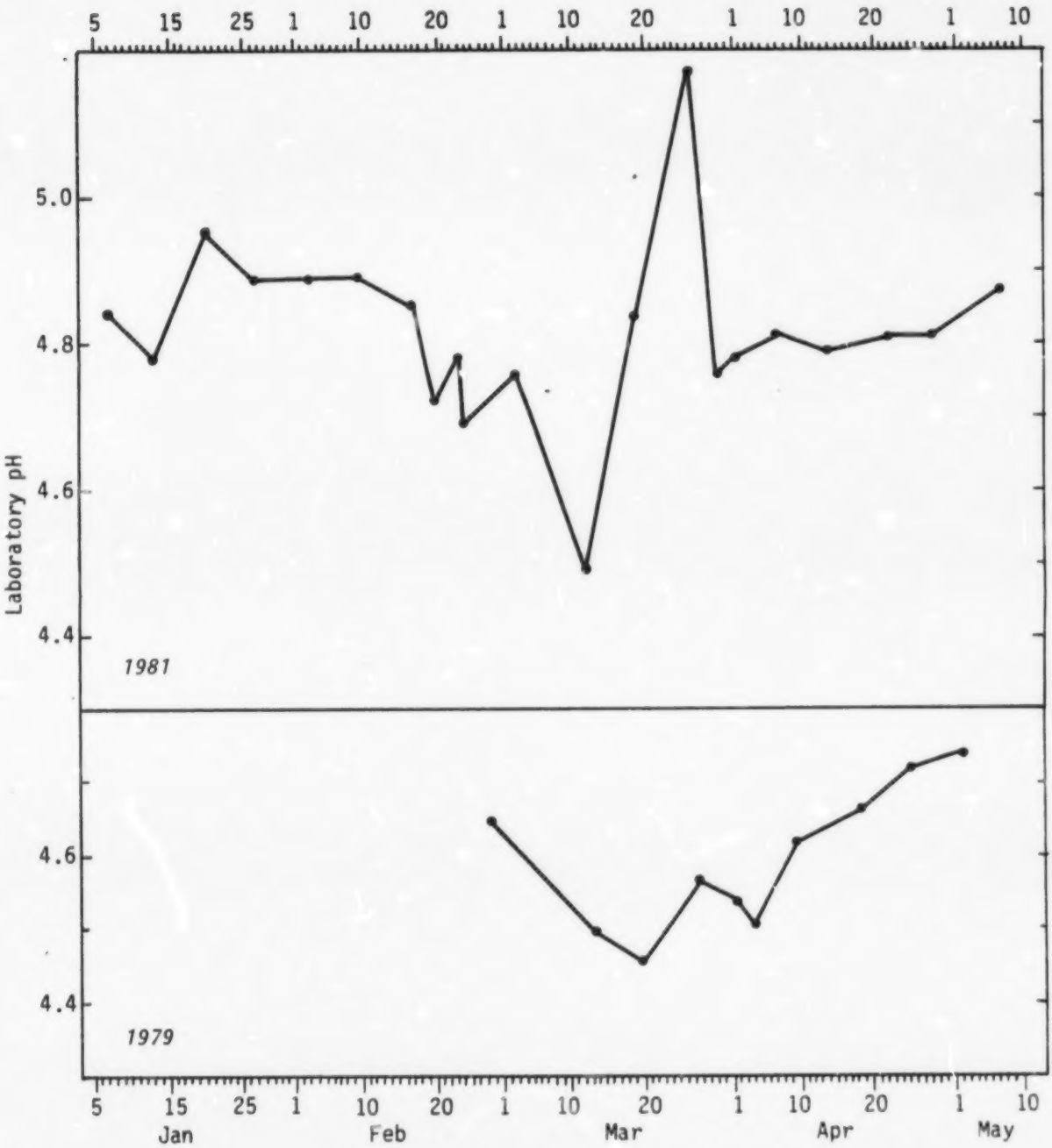

FIGURE 1

DICKIE LAKE INLET #10: LABORATORY
pH, SPRING 1979 AND 1981

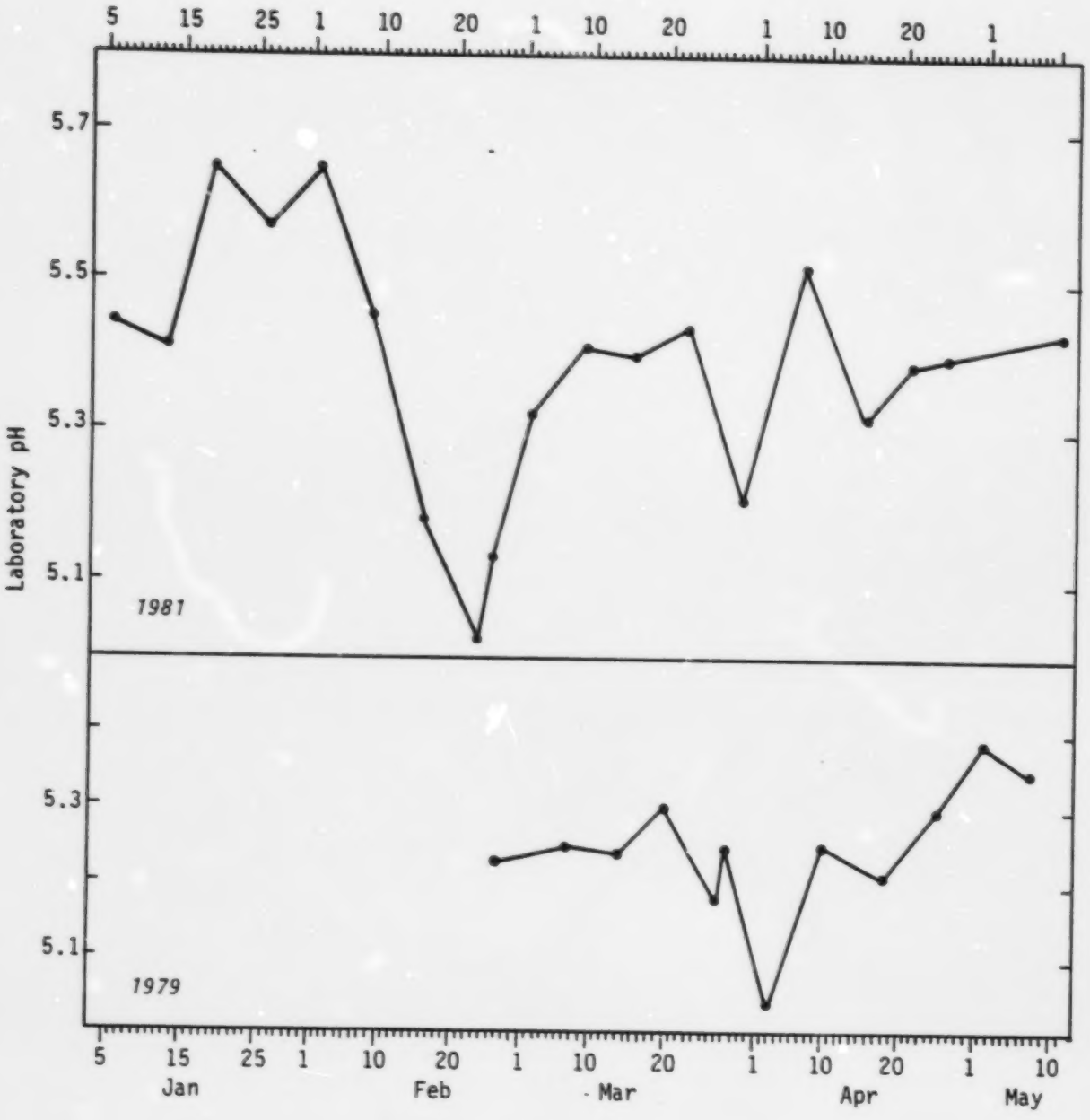

FIGURE 2

PAINT LAKE INLET #1: LABORATORY
pH, SPRING 1979 AND 1981

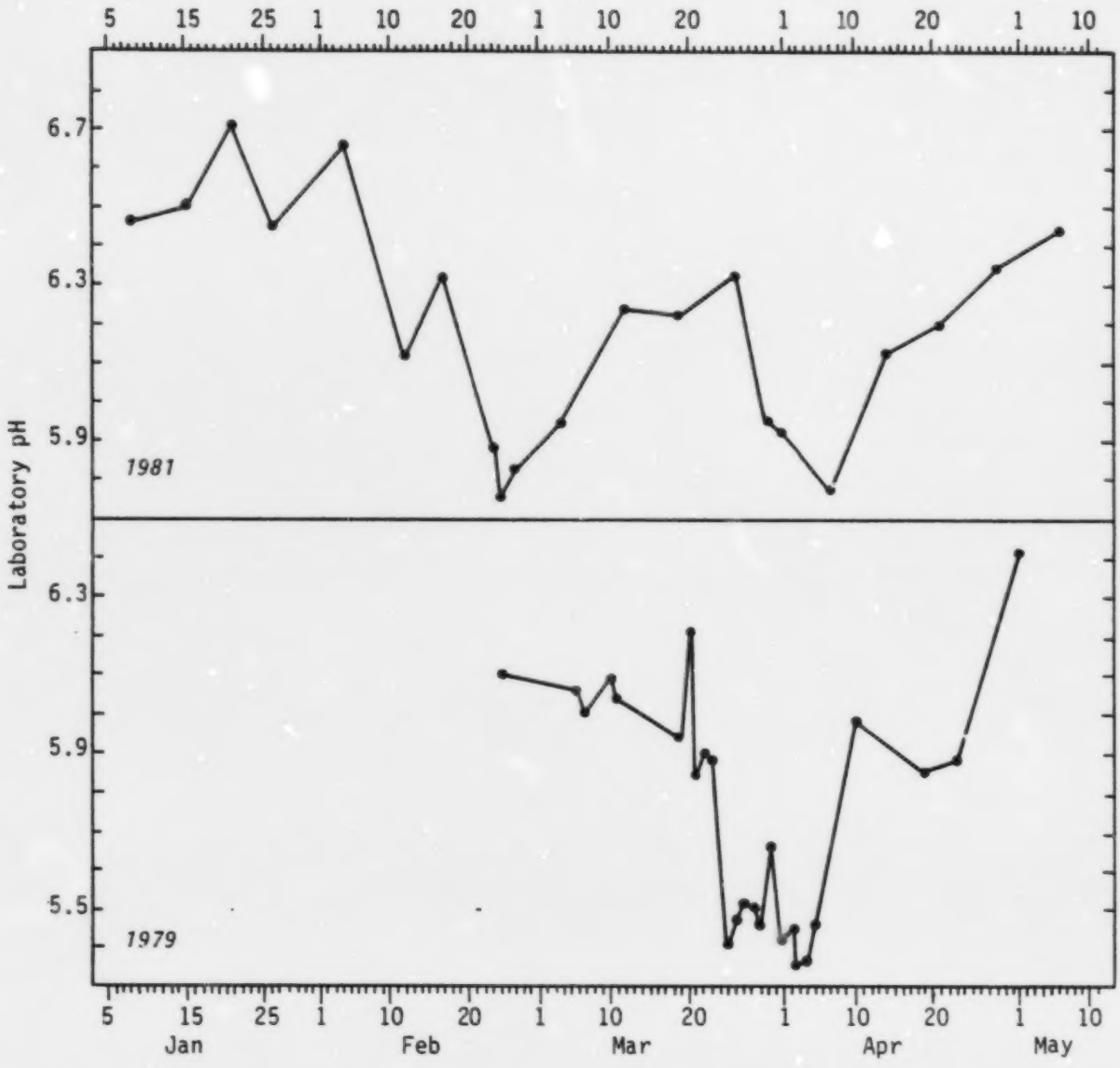

FIGURE 3

HARP LAKE INLET #4: LABORATORY
pH SPRING 1979 AND 1981

investigators in spring 1978 (Jeffries, Cox and Dillon, 1979). However, the only stream in the set with a normal pH close to neutrality (Harp Lake inlet 4, pH ~6.4), had a pH depression of 0.9 pH units in 1979 (maximal $[H^+] = 4.0 \times 10^{-5}$) and 0.7 units in 1981 (maximal $[H^+] = 1.6 \times 10^{-6}$). The roughly threefold greater maximal $[H^+]$ in 1979 than in 1981 may have been more damaging to fish eggs, especially those spawned in nearly neutral water. Furthermore, the 1981 spring pH minimum occurred in late February, whereas that in 1979 occurred in early April. The later depression may be more harmful to fish eggs for two reasons (J.S. Griffiths, Ontario Hydro, private communication; J. Monroe, Ontario Ministry of the Environment, private communication):

(i) The recovery of pH to normal levels from an early April minimum may take long enough that eggs of spring-spawning species such as rainbow trout are affected.

(ii) The eggs of fall-spawning species (such as lake trout and brook trout) which may experience the late February depression go through developmental stages of greater or lesser robustness of the embryo. The embryo is sensitive to stress at the early and late stages of development and relatively insensitive in intermediate stages. The times of occurrence of these stages differ widely between species and within a species under different conditions, but are a factor determining the response of fish populations to chemical stress.

Thus, the effect of the pH depression upon fish populations depends upon the time as well as the magnitude of the depression. The timing of the runoff is a purely meteorological effect, while the magnitude of the depression is a chemical phenomenon which may or may not be significantly influenced by cumulative event meteorology.

These considerations illustrate that a complicated biological effect such as fish embryo mortality is unlikely to be related directly to a simple chemical parameter such as snowpack H^+ load. Time dependence of the biological responses to chemical variations, neutralization by minerals, and biological uptake of nutrient ions all have a significant effect. Nonetheless, atmospheric transport and transformation of pollutants do play an extremely important part in the process. This study of the chemical and meteorological aspects of the major snow precipitation events of 1978-79 and 1980-81 was initiated in order to gain insight into the origins of the meltwater ionic loads and to investigate connections between meteorological and chemical variables.

3.2 Meteorological Data; Event Selection Criteria

Because the principal objective of this work is to study the origin of pollutants in the snowpack in an environmentally sensitive area, events were selected on the basis of contribution to snowpack depth at the Muskoka airport weather station. The Muskoka region is roughly 180 km north of the Toronto-Hamilton industrial area, 210 km southeast of the Sudbury smelters, 470 km northeast of the

Detroit-Windsor area, 780 km northeast of the lower Ohio valley, and 350 km south of the smelters at Rouyn, Quebec. The region contains a large number of lakes susceptible to acidification (Scheider, Jeffries and Dillon, 1979).

For the winters of 1978-79 and 1980-81 the snowstorms were ranked according to the increase in ground snow depth which occurred during the storm. This criterion tends to reject storms during relatively warm periods which deposit large water equivalents of snow without increasing the snow depth significantly. It tends to retain storms during cold periods which deposit a comparatively large depth but low water equivalent of loose, powdery snow. This bias is probably aporopriate because snow deposited in colder periods tends to be incorporated in the snowpack, whereas snow deposited in warm periods may melt quickly and drain without becoming part of the snowpack.

Contributions to snowpack depth are assessed as follows: At 7:00 am EST (12Z GMT) each day the surface snow depth in cm is measured at the Muskoka airport weather station. If it has increased over the past 24 hours, the rise is ascribed to the snowfall event occurring in that period. When two different snowfalls (separated by at least six hours) occur in the previous day, the depth rise is partitioned between events using the 6-hourly precipitation type and water-equivalent depth data for the periods 1:00 am-7:00 am (06-12Z), 7:00 am-1:00 pm (12-18Z), 1:00 pm-7:00 pm (18-24Z) and 7:00 pm-1:00 am (00-06Z).

This method of quantifying the contribution of a snowfall event to the snowpack is subject to several problems. Some of the observed rise may be due to blowing snow rather than to newly-fallen snow, and melting or sublimation in the days following an event may cause the contribution to the snowpack to be overestimated from the depth rise measured immediately after the event. However, it is difficult to formulate a more accurate indication of a storm's contribution to the snowpack which uses only readily available meteorological data.

An explicit statement of the event selection process is as follows. All snow depth increases were identified from the weather station records and summed to yield a winter's total depth rise. Events were then arranged in order of decreasing depth rise (measured to the nearest cm) to include at least 75% of the winter's total rise. All events of equal depth rise are retained so that if, for example, events dropping 8 cm or more of snow account for 72% of the total rise and events dropping 7 cm or more account for 77%, events through 7 cm are retained. Other meteorological data used to define snowfall events and to partition depth rise between events include the daily minimum and maximum temperatures, daily and 6-hourly water equivalents of rain and snow, and the detailed classification of all precipitation types falling in a 24-hour period.

3.3 Events Selected

Snow depth and snowfall data for 1978-79 and 1980-81 are plotted in Figure 4. The major events selected using these data and the criteria specified in the preceding paragraph are specified in Tables 2 and 3.

Note that:

(i) The snowpack became considerably deeper in 1978-79 than in 1980-81 (100 cm vs 63 cm).

(ii) There were more heavy snowfalls in 1978-79, with three events in that winter equalling or exceeding the largest in 1980-81.

(iii) Major storms in 1978-79 were concentrated in January, while in 1980-81 the dominant month was December, with more than 50% of the total snow depth rise occurring before December 20.

(iv) The major spring melt of 1981 occurred in mid-February, with a rapid and total disappearance of the snowpack between February 16 and 25. In 1972 the snow depth decreased gradually from mid-February through early April, with the sharpest decreases in late March.

3.4 Chemical Analyses of Precipitation

No chemical analyses of precipitation samples on an event basis for the Muskoka region was performed in 1978-79. During the winter of 1980-81 the Ontario Ministry of the Environment collected and analyzed event samples at the Dorset site in Muskoka as part of the Acid Precipitation in Ontario Study (APIOS). The analytical results for July, 1980-December, 1981 have been issued as a report (Ontario Ministry of the Environment, 1982). The Dorset site is roughly 50 km northeast of the Muskoka airport site at which the meteorological data discussed in the preceding section were collected.

The lack of event chemical data for 1978-79 makes a comparison between the two winters based on snowfall event sampling impossible. However, Jeffries and Snyder (1982) presented analyses both of snow-cores and of cumulative bulk deposition in Muskoka in both 1979 and 1981, which allows a comparison. Interpretation of the 1978-79 snowpack composition on the basis of air parcel trajectories is of limited value because of the lack of time-resolved composition data. The bulk deposition data for H^+, SO_4^{2-}, and NO_3^- for 1978-79 given by Jeffries and Snyder (1982) are listed in Table 4.

Analytical results from the APIOS report for $[SO_4^{2-}]$, $[NO_3^-]$, and $[H^+]$ in samples corresponding to the events listed in Table 3 are given in Table 5, along with deposition data from Jeffries and Snyder (1982). Events 4 and 5 and events 8 and 9 were lumped; that is, only a single sample for each pair of events was collected and analyzed.

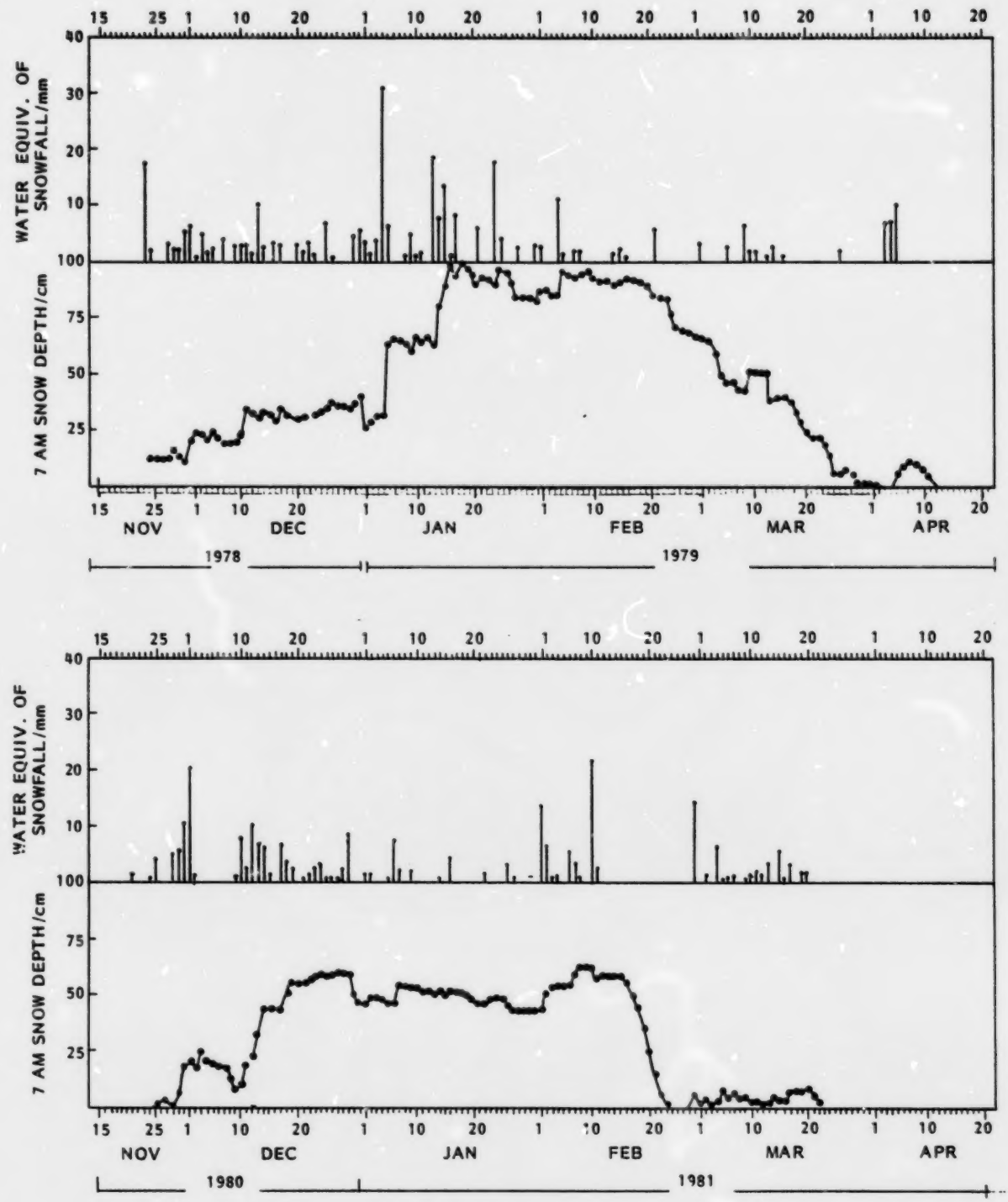

FIGURE 4

SNOWPACK DEPTH AND WATER EQUIVALENT OF SNOWFALL
MEASURED AT MUSKOKA AIRPORT, WINTER 1978-79 AND 1980-81

Table 2. Major snowstorms of 1978-79, chosen by increase in ground snow depth. These 13 events accounted for 78% of the season's total rise in snowpack depth ordered chronologically.

Event	Time (EST)	Snowpack rise (cm)
1	10 AM 23 Nov - 7 AM 24 Nov 1978	13
2	Noon 30 Nov - 9 AM 1 Dec 1978	8
3	10 PM 10 Dec - 1 PM 11 Dec 1978	14
4	3 AM 30 Dec - 1 PM 31 Dec 1978	5
5	10 AM 4 Jan - 1 PM 5 Jan 1979	33
6	7 AM 9 Jan - 9 PM 9 Jan 1979	5
7	11 AM 13 Jan - 2 PM 14 Jan 1979	27
8	4 AM 15 Jan - 10 PM 15 Jan 1979	9
9	3 AM 17 Jan - 11 PM 17 Jan 1979	6
10	10 AM 24 Jan - 2 PM 25 Jan 1979	7
11	4 AM 4 Feb - 7 AM 5 Feb 1979	10
12	6 PM 9 Mar - 6 PM 10 Mar 1979	7
13	7 PM 4 Apr - 5 AM 5 Apr 1979	7
Total, 13 events		151 (78%)
Total, winter		193

Table 3. Major snowstorms of 1980-81, chosen by increase in ground snow depth. These 15 events accounted for 80% of the season's total snowpack rise ordered chronologically.

Event	Time (EST)	Snowpack rise/cm
1	2 PM 28 Nov - 10 AM 29 Nov 1980	5
2	4 PM 29 Nov - 2 PM 30 Nov 1980	14
3	3 AM 2 Dec - 2 AM 3 Dec 1980	7
4	4 AM 10 Dec - 6 PM 10 Dec 1980	11
5	7 AM 11 Dec - 5 PM 11 Dec 1980	4
6	7 AM 12 Dec - 2 PM 13 Dec 1980	10
7	8 PM 13 Dec - 8 AM 14 Dec 1980	9
8	8 PM 17 Dec - 5 AM 18 Dec 1980	10
9	6 PM 18 Dec - 4 AM 19 Dec 1980	5
10	Noon 6 Jan - 8 AM 7 Jan 1981	8
11	Noon 1 Feb - 3 PM 2 Feb 1981	10
12	9 AM 6 Feb - 8 PM 6 Feb 1981	5
13	2 AM 28 Feb - 6 PM 28 Feb 1981	5
14	2 AM 4 Mar - 8 PM 4 Mar 1981	5
15	3 PM 15 Mar - 1 AM 16 Mar 1981	4
Total, 15 events		112 (80%)
Total, winter		140

Table 4. Winter 1978-79: Chemical composition of Muskoka snowcore and bulk precipitation samples (Jeffries and Snyder, 1982)

	Concentrations, μeq/L					
	$[NO_3^-]$	$[SO_4^{-2}]$	$[H^+]$	$([SO_4^{-2}]+[NO_3^-])$	pH	$[SO_4^{-2}]/[NO_3^-]$
Bulk - Cumulative to: Feb 21, 1979	32.0	37.0	83.0	69.0	4.08	1.16
Snowcore - taken: Feb 21, 1979	37.0	20.0	56.0	57.0	4.25	0.54

Table 5: Winter 1980-81: Chemical composition of Muskoka event (OME, 1982) and cumulative bulk (Jeffries and Snyder, 1982) precipitation samples and snowcore samples (Jeffries and Snyder, 1982)

Event	Sample Volume, ml	Gauge depth, mm	Concentrations, μeq/L					
			$[NO_3^-]$	$[SO_4^{=}]$	$[H^+]$	$([SO_4^{=}]+[NO_3^-])$	pH	$[SO_4^{=}]/[NO_3^-]$
1	610	5.0	29.3	19.8	46.0	49.1	4.34	0.68
2	126	1.2	16.4	22.9	37.0	39.3	4.43	1.40
3	1251	34.8	12.1	21.8	34.0	33.9	4.47	1.80
4, 5	190	4.8	8.6	11.4	20.0	20.0	4.69	1.32
6	347	6.6	22.1	16.6	28.0	38.7	4.55	0.75
7	227	6.2	12.9	11.4	17.0	24.3	4.76	0.88
8, 9	440	10.8	27.1	16.6	33.0	43.7	4.48	0.61
10	369	7.4	35.7	7.3	46.0	43.0	4.34	0.20
11	1312	23.2	27.1	20.8	41.0	47.9	4.39	0.77
12	41	2.6	85.0	21.8	89.0	106.8	4.05	0.26
13	362	6.9	32.8	33.3	39.0	66.1	4.41	1.02
14	41	3.4	85.7	17.7	85.0	103.4	4.07	0.21
15	230	4.7	42.8	45.8	16.0	88.6	4.80	1.07
Volume-weighted average:	5546*		24.6	20.6	37.0	45.2	4.43	0.84
Median			28.0	20.0	38.0	44.0	4.42	0.80
Bulk - Cumulative to:								
Jan 13, 1981			44.0	28.0	50.0	72.0	4.30	0.64
Jan 20, 1981			45.0	30.0	53.0	75.0	4.28	0.67
Feb 8, 1981			47.0	34.0	58.0	81.0	4.24	0.72
Feb 17, 1981			46.0	36.0	62.0	82.0	4.21	0.78
Snowcores - Taken:								
Jan 13, 1981			28.0	18.0	37.0	47.0	4.43	0.64
Jan 20, 1981			33.0	17.0	48.0	50.0	4.32	0.51
Feb 8, 1981			30.0	19.0	59.0	49.0	4.23	0.63
Feb 17, 1981			29.0	21.0	45.0	50.0	4.35	0.72
			Total amounts collected, μeq**					
1			17.9	12.1	27.9	30.0		
2			2.1	2.9	4.7	5.0		
3			15.1	27.3	42.4	42.4		
4, 5			1.6	2.2	3.9	3.8		
6			7.7	5.8	9.8	13.4		
7			2.9	2.6	4.0	5.5		
8, 9			11.9	7.3	14.6	19.2		
10			13.2	2.7	16.9	15.9		
11			35.6	27.3	53.4	62.8		
12			3.5	0.9	3.7	4.4		
13			11.9	12.1	14.1	23.9		
14			3.5	0.7	3.5	4.2		
15			9.8	10.5	3.6	20.4		
Median			10.0	5.8	10.0	16.0		

* Total
** Sample volumes times concentrations

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The analytical data represent a volume-weighted average of the two lumped events. This decreases the effective number of events for study in 1980-81 from 15 to 13. Total ion deposition per event is also shown in Table 5.

3.5 Emissions

No attempt is made in this work to model explicitly the transport, transformation, and deposition of pollutants during the selected events, and therefore detailed emissions data are not strictly necessary for this study. However, it is of general interest to relate the levels of pollutant emission to precipitation ionic content, and for that reason some relevant emissions data for 1978-79 and 1980-81 are surveyed here.

Emissions of SO_2 and NO_2 in a typical year (1980), for the Toronto-Hamilton, Detroit-Windsor, Lower Ohio Valley, Sudbury, and Rouyn regions are given in Table 6, as compiled by the Canada-US Memorandum of Intent Committee (Rivers and Riegel, 1983). Although these numbers are not specific to the winter studied, they serve to show typical relative emission rates in the regions contributing most to the ionic loading of precipitation in the Muskoka region.

Detailed emissions information is available for fossil-fuel fired generating stations operated by Ontario Hydro. Monthly emissions of SO_2 and NO_2 from these stations are listed in Table 7 for 1978-79 (Reeves, 1979; Cross, 1980) and in Table 8 for 1980-81 (Reeves, 1981; Perks, 1982).

In Table 9 SO_2 emissions from Sudbury (INCO and Falconbridge) are given for 1978-79 and 1980-81.

From September, 1978 until June, 1979, the INCO smelters at Sudbury were strikebound; during this period (including the entire winter of 1978-79) the normally high SO_2 emissions from this source were reduced essentially to zero.

3.6 Overview of Data

1. Snowfall: there was greater total snowfall in 1978-79 than in 1980-81, and it remained on the ground until late March, while in 1980-81 the major melt occurred over a week-long span in mid-February.

2. Chemical Analysis: the single 1978-79 snowcore sample had roughly the same composition as the average of the 1980-81 cores, with slightly higher nitrate in 1978-79. The cumulative bulk deposition in 1978-79 had both higher H^+ concentration and lower sulfate and nitrate contents than did the 1980-81 samples, but it is impossible to tell whether this is characteristic of the two years or an artifact of the single sample for 1978-79. Snowcore concentrations are less than those in bulk deposition.

Table 6: Emissions of SO_2 and NO_2 during 1980 from regions likely to contribute to deposition in Muskoka. Data from Rivers and Riegel (1983).

Region	Emissions, kilotonnes/year	
	SO_2	NO_2
Detroit - Windsor	318.1	105.4
Toronto - Hamilton	250.6	160.9
Sudbury	939.9	10.
Ohio Valley	10 180.	2 000.
Rouyn, Quebec	484.9	0.

Table 7. Monthly emissions of SO_2 and NO_2 from fossil-fuel fired generating stations operated by Ontario Hydro, Winter 1978-79. Values in kilotonnes.

Station \ Month	1978						1979								TOTAL	
	OCT		NOV		DEC		JAN		FEB		MAR		APR			
	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2
Hearn	0.004	0.5	0.001	0.5	0.001	0.6	1.0	1.	1.8	1.	0.37	0.6	0.024	0.6	3.2	6.
Lakeview	6.6	1.	9.	2.	11.	2.	13.	3.	15.	3.	8.5	2.	7.3	2.	70.	20.
Thunder Bay	0.88	0.2	0.44	0.1	0.61	0.1	0.72	0.1	0.87	0.1	0.94	0.2	0.97	0.2	5.4	1.
Lambton	12.	1.	8.2	1.	13.	2.	19.	3.	17.	2.	13.	2.	10.	2.	92.	10.
Nanticoke	19.	4.	19.	4.	21.	5.	23.	6.	24.	6.	18.	4.	18.	4.	140.	30.
Lennox	0.81	0.1	1.9	0.3	3.4	0.6	5.9	0.8	3.7	0.5	0.21	0.07	0.005	0.02	16.	2.
Keith	0	0	0	0	0	0	0.0004	0.002	0.0003	0.001	0.0002	0.0009	0.0002	0.0006	0.001	0.005
Total	39.	7.	39.	8.	49.	10.	63.	10.	62.	10.	41.	9.	36.	9.	330.	70.

TABLE 8. Monthly emissions of SO_2 and NO_2 from fossil-fuel fired generating stations operated by Ontario Hydro, Winter 1980-81. Values in kilotonnes.

Month	1980						1981								TOTAL	
	OCT		NOV		DEC		JAN		FEB		MAR		APR			
Station	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2
Hearn	1.0	0.2	1.1	0.3	0.72	0.3	1.9	0.6	0.93	0.3	0.36	0.2	0.080	0.080	6.1	2.
Lakeview	6.9	2.	7.2	2.	9.1	2.	16.	5.	6.3	2.	4.8	2.	4.6	2.	55.	20.
Thunder Bay	0.76	0.1	0.94	0.2	0.65	0.1	0.61	0.2	0.33	0.08	0.38	0.08	0.96	0.2	4.6	1.
Lambton	12.	2.	13.	2.	16.	2.	19.	3.	13.	2.	12.	2.	12.	2.	97.	20.
Nanticoke	13.	5.	13.	5.	17.	7.	24.	10.	13.	6.	12.	5.	12.	5.	100.	40.
Lennox	0.0088	0.003	0.030	0.01	0.12	0.04	0.66	0.2	0.27	0.08	0.030	0.02	0.020	0.008	1.1	0.4
Keith	0.066	0.01	0.062	0.02	0.098	0.03	0.24	0.06	0.13	0.03	0.27	0.06	0.33	0.08	1.2	0.3
Total	34.	9.	35.	10	44.	10.	62.	20.	34.	10.	30.	9.	30.	9.	270.	80.

Table 9. Subdury Smelter Emissions, Winters 1978-79 and 1980-81. Values in Kilotonnes

	1978 (a)			1979 (a)				
	OCT	NOV	DEC	JAN	FEB	MAR	APR	TOTAL
	SO_2	SO_2	SO_2	SO_2	SO_2	SO_2	SO_2	SO_2
INCO (b)	0	0	0	0	0	0	0	0
Falconbridge	10	10	10	7	7	7	7	58
TOTAL	10	10	10	7	7	7	7	58

	1980 (a)			1981 (a)				
INCO	68	68	68	60	60	60	60	444
Falconbridge	10	10	10	10	10	10	10	70
TOTAL	91	91	91	81	81	81	81	514

(a) monthly values calculated as one-twelfth of yearly values to facilitate comparison with Tables 7 and 8.

(b) Strikebound Sept 1978 - June 1979.

3. Emissions: despite the fact that the 1978-79 INCO strike caused SO_2 emissions from Sudbury to be considerably lower for 1978-79 than in 1980-81, emissions of SO_2 both from Ontario Hydro and from all of eastern North America were lower in 1980 and 1981 than in 1978 and 1979. The historical trend has been that SO_2 emissions increased annually until about 1970 and have decreased subsequently; NO_x emissions increased until about 1970 and have remained essentially constant since then (National Academy of Sciences, 1983).

4.0 AIR PARCEL TRAJECTORIES

The air parcel trajectories used for this work were calculated by M. Olson and K. Oikawa of the Atmospheric Environment Service. For each of the selected storms, backward air parcel trajectories originating at the Muskoka airport were calculated at three different times, corresponding roughly to the beginning, middle, and end of the snowfall. At each of these times, trajectories were started at four different altitudes. The parameters specifying the trajectory calculations are listed in Table 10.

The method used for the trajectory calculations (designated the ARQT method) has been described in detail by Olson et al (1978). Briefly, horizontal wind fields are computed by interpolation of radiosonde wind data at upper levels (850, 700, and 500 mb) and from the calculated geostrophic wind field with a frictional turning term added at 1000 mb. Vertical wind speeds at the 850, 700, and 500 mb levels are calculated using an ω-equation approach developed by Haltiner et al (1963) which allows the air parcel to descend in high-pressure systems and ascend in low-pressure systems. Vertical winds at the 1000 mb level are calculated on the basis of terrain and frictional effects.

Because wind and pressure data are taken from the 381 km grid used by the Canadian Meteorological Centre (CMC) they are available directly only at these grid points and at the 500, 700, 850, and 1000 mb levels. The values at points along a trajectory must be determined by interpolation. Interpolation in the ARQT model is cubic in the vertical and linear in the horizontal coordinates, with interpolations in time, if needed, between the 6-hourly points in the CMC data done quadratically.

Because many methods calculated isobaric trajectories, with no possibility of vertical motion, it is emphasized that the air parcel trajectories generated for this work include vertical motion on the synoptic scale. The pressure which identifies the trajectory is its initial pressure at the receptor location (Muskoka); as the parcel is followed backward in time it rises as it traverses low pressure systems and falls as it traverses highs. The vertical motions are on the synoptic scale only; the vertical motions due to convection are not taken into account.

Table 10: Parameters specifying the air-parcel trajectories calculated for the events listed in Tables 2 and 3. All trajectories were calculated backward from the initial point.

Initial location: 44° 58' N, 79° 18' W (Muskoka Airport)

Initial Levels:

Pressure	Altitude
1000 mb	Surface
925 mb	500 m
850 mb	1000 m
700 mb	3000 m

Time increments: 6 h/step, 12 steps/trajectory, 72 h/trajectory.

Three initial trajectory times for each storm: roughly beginning, middle and end.

The air parcel trajectories initially at 925 mb were chosen to represent the transport of polluted air, since this altitude (roughly 0.5 km) represents approximately the mid-altitude of the polluted layer. Ascent or descent of the parcel as the trajectory evolves weakens this argument, but since the vertical motions are relatively slow, this choice seems best unless a case-by-case choice of representative trajectories is done.

The effect upon the computed trajectory of the choice of initial altitude is illustrated in Figure 5 for one event in 1978-79 and in Figure 6 for one event in 1980-81.

Note that:

(i) at higher levels the trajectories are longer (wind speeds higher)

(ii) the trajectories tend to veer (shift clockwise) with increasing altitude.

(iii) the spread of wind directions over a given time interval tends to be greater at low altitudes.

The 925 mb trajectories calculated for the 13 events of 1978-79 (Table 2) are mapped in Appendix 1 (Figures A1-1 through A1-13); trajectories for the 15 events of 1980-81 (Table 3) are mapped in Appendix 2 (Figures A2-1 through A2-15).

5.0 METHOD OF DATA ANALYSIS

With data so diverse and variable as stream pH values, air parcel trajectories, snowpack compositions, and chemical analyses of precipitation, it is inevitable that no single analysis can relate all of the variables.

The approach adopted here is to concentrate upon the data which are fairly numerous and complete, namely the air parcel trajectories and the chemical analyses of precipitation for the major events of 1980-81.

5.1 Trajectory Direction of Origin

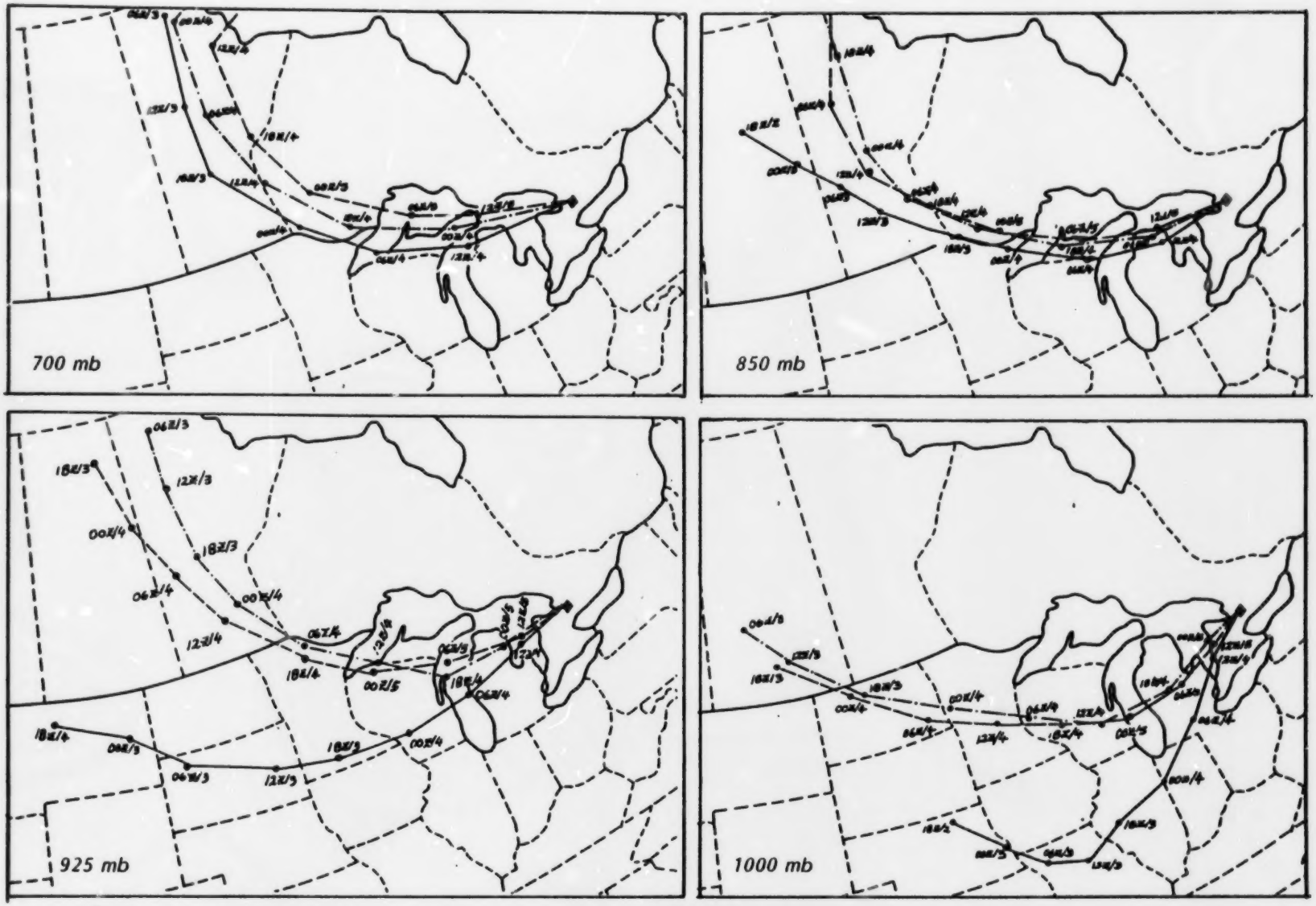
The 925 mb air parcel trajectories, consisting of points 6 hours apart, are classified by direction of origin as follows:

(i) Points in the first 48 hours of the back-trajectory are considered.

(ii) The trajectory is classed as northerly (N) if:

  (a) at most two points of the trajectory lie south of the receptor

  (b) no point is south of the receptor by more than 0.5 degrees of latitude



—— 18Z Jan 2 - 18Z Jan 4 1979
-·-· 06Z Jan 3 - 06Z Jan 5 1979
---- 18Z Jan 3 - 18Z Jan 5 1979

FIGURE 5

1978-79, EVENT 5. BACKWARD AIR PARCEL TRAJECTORIES FROM MUSKOKA AT 4 INITIAL ALTITUDES, 3 INITIAL TIMES

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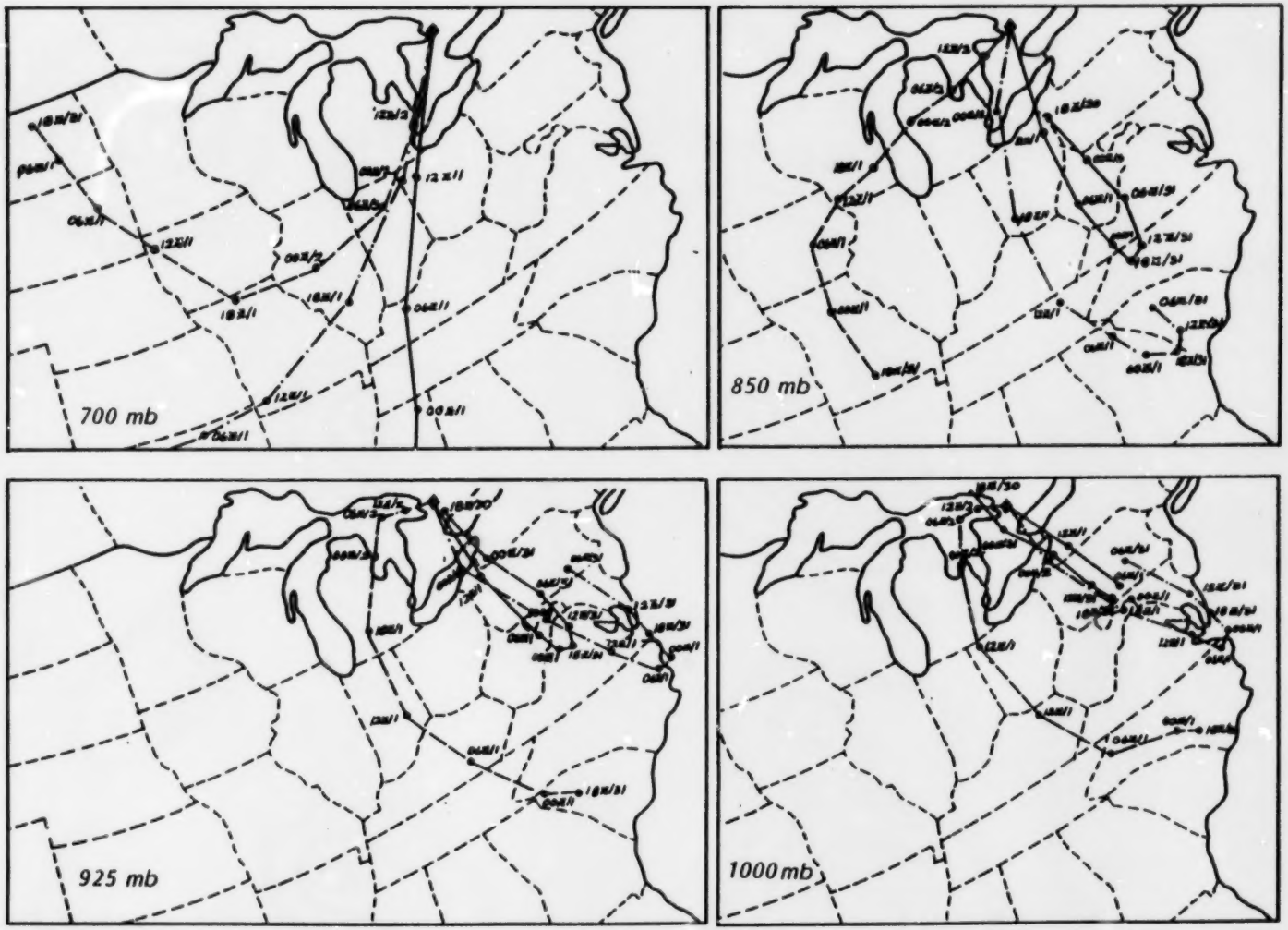
165361 RD



18Z Jan 30 - 18Z Feb 1 1981
06Z Jan 31 - 06Z Feb 2 1981
18Z Jan 31 - 18Z Feb 2 1981

FIGURE 6

1980-81, EVENT 11. BACKWARD AIR PARCEL TRAJECTORIES FROM MUSKOKA AT 4 INITIAL ALTITUDES, 3 INITIAL TIMES

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165362 RD

(iii) The trajectory is classed as southerly (S) if:

(a) at most two points of the trajectory lie north of the receptor

(b) no point is north of the receptor by more than 0.5 degrees of latitude.

(iv) A trajectory neither N nor S is classed as mixed (M).

5.2 Event Direction of Air Parcel Origin

The trajectories corresponding to the three initial times chosen for a given event are classified as N, S, or M as specified in the preceding section. The event as a whole is classified as N, S, or M as follows:

(i) An event is classed as N if

(a) all three trajectories are N; or

(b) two trajectories, including that at the middle time, are N or

(c) the initial and final trajectories are N and the middle M.

(ii) An event is classed as S by the same criteria as in (i) with S replacing N throughout.

(iii) An event not N or S is classed as M.

Classification of the 1978-79 and 1980-81 trajectories and events by these criteria are given in Table 11.

Because the chemical analyses are reported for combined samples for events 4 and 5 and 8 and 9 of 1980-81, the event classifications are combined for these pairs. Of this reduced set of 13 events, 7 are S, 2 are N, and 4 are M.

5.3 Meteorological and Chemical Variables

The variables discussed here are the precipitation amount (measured in three different ways), and the chemical variables $[NO_3^-]$, $[SO_4^=]$, $[H^+]$, $([SO_4^=]+[NO_3^-])$, and $[SO_4^=]/[NO_3^-]$. The summed sulfate and nitrate concentration is included as a distinct quantity because comparison of this quantity with $[H^+]$ indicates to what extent the potential sulfate and nitrate acidity in the precipitation is neutralized.

These variables assume a continuous range of values and must be classified according to magnitude. In this work, the classification consisted of dividing the set of magnitudes of one variable over all 13 events into an upper cut of 6 and a lower cut of 7 values. This is equivalent to determining a median value for the variable and classifying events by whether the variable value exceeds the median.

Table 11: Trajectory and event directions of air-parcel origin, 1978-79 and 1980-81.

1978-79:

Event # (b)	Classification (a)			
	Trajectory			Event
	Time 1	Time 2	Time 3	
1	S	S	M	S
2	N	N	M	N
3	N	M	S	M
4	M	S	S	S
5	M	N	N	N
6	M	M	S	M
7	S	S	N	S
8	N	N	M	N
9	N	S	M	M
10	S	S	N	S
11	S	N	N	N
12	S	S	M	S
13	N	M	N	N

(a) N: flow from north; S: flow from south; M: mixed flow

(b) Table 2

1780-81:

Event # (c)	Classification (a)			
	Trajectory			Event
	Time 1	Time 2	Time 3	
1	S	S	M	S
2	N	M	M	M
3	S	S	N	S
4	N	N	N	N
5	N	N	N	
6	M	S	N	M
7	N	M	N	N
8	M	S	S	M
9	N	N	N	
10	S	S	S	S
11	S	S	S	S
12	S	S	M	S
13	M	S	S	S
14	N	M	S	M
15	S	S	N	S

(c) Table 3

A similar classification could be done with the mean rather than the median value, but the median has two advantages: (i) a single anomalously large value in a set may affect the mean value significantly but affects the median at most only slightly; (ii) for a fixed number of events the median classification produces upper and lower sets always containing the same number of events (6 and 7 in this case). Above- and below-mean sets do not have this property. Having the numbers constant facilitates the statistical analysis somewhat.

The three ways of measuring snowfall amount are snowpack rise (Table 3), gauge depth of precipitation recorded at Dorset (OME, 1982), and volume collected in the APIOS precipitation sampler at Dorset (Table 5). The reduced set of 13 events for 1980-81 are classified as being in the higher (H) cut of 6 or the lower (L) cut of 7 for these three measures of precipitation amount, as well as for the chemical variables, in Table 12.

5.4 Assessing Correlations: Meteorological and Chemical Variables with Air Parcel Direction

For each variable the correlation on an event basis with air parcel direction of origin is assessed as follows:

1. The events of mixed (M) air parcel origin are combined with the S or the N events to give a set of 13 events classed either as S or N. Both combinations were tried.

2. Of the six events in the higher (H) cut of the variable in question, the number with direction S are counted.

3. The probability that a random selection of six events would have this distribution of S and N is calculated.

4. If a random draw would produce the observed distribution in more than a certain fraction of cases (usually 5%), the hypothesis. of a correlation between the variable being in the upper cut and the air parcel being of a given origin is rejected.

The probabilities are calculated from the hypergeometric distribution. The sampling is equivalent to drawing m balls at random from an urn containing k balls, with n balls marked N and s balls marked S (n and s corresponding to the numbers of events of these originals); the probability of drawing x balls marked S in a sample of m is given by the hypergeometric expression

$$P(s,n)_x^m = \frac{\binom{s}{x}\binom{n}{m-x}}{\binom{n+s}{m}}$$

where the braces indicate the binomial coefficient.

TABLE 12

Classification of 1980-81 events as being in the higher (H) or lower (L) cut of the values of the meteorological and chemical variables

Event	R[a]	V[b]	D[c]	$[NO_3^-]$	NO_3^-T[d]	$[SO_4^{=}]$	$SO_4^{=}T$	$[H^+]$	$H^+{}_T$	S+N[e]	$(S+N)_T$	S/N[f]
1	L	H	L	H	H	L	H	H	H	H	H	L
2	H	L	L	L	L	H	L	L	L	L	L	H
3	L	H	H	L	H	H	H	L	H	L	H	H
4 5	H	L	L	L	L	L	L	L	L	L	L	H
6	H	L	H	L	L	L	L	L	L	L	L	L
7	H	L	L	L	L	L	L	L	L	L	L	H
8 9	H	H	H	L	H	L	H	L	H	L	H	L
10	L	H	H	H	H	L	L	H	H	L	L	L
11	H	H	H	L	H	H	H	H	H	H	H	L
12	L	L	L	H	L	H	L	H	L	H	L	L
13	L	H	H	H	H	H	H	H	H	H	H	H
14	L	L	L	H	L	L	L	H	L	H	L	L
15	L	L	L	H	L	H	H	L	L	H	H	H

a Snowpack Rise

b Precipitation Sample Volume

c Precipitation Gauge Depth

d Total NO_3^-

e $[SO_4^{=}] + [NO_3^-]$, μeq/L

f $[SO_4^{=}]/[NO_3^-]$, μeq/L

For the 1980-81 event analysis m = 6 and k = 13, with s = 11, n = 2 if m is combined with s and s = 7, n = 6 if m is combined with n, as seen from Table 11. For these two choices of n and s the probabilities P_x^m are listed in Table 13, along with the cumulative probabilities that x or fewer or x or more of designation S are drawn. These cumulative probabilities are the relevant quantities in assessing whether a given distribution is likely to be obtained randomly.

5.5 Assessing Correlations Between Pairs of Meteorological or Chemical Variables

The partition of the events into upper and lower cuts according to values of the variables (Table 12) is used to assess the correlation between variables as follows:

1. For a given event two variables are classed as coupled (C) either if both variables are in the lower cut (L) for the event or if both are in the higher cut (H) for the event.

2. The number of couples over the whole set of events is counted for each pair of variables.

3. The degree of correlation between the pair of variables is assessed by calculating the probability of obtaining the observed number of couples in a random draw of two sets of 13 events, each set having 6H and 7L.

The probability is again calculated from the hypergeometric distribution. The sampling problem is equivalent to drawing six balls from an urn containing 13 balls (6H and 7L), to match to the six H members of a previously chosen set. The number of couples in this draw of six fully determines the number of couples in the full draw of 13, since k couples in the set of six insure 2k+1 overall. Then the probability of drawing 2k+1 couples in two sets of 13 is given by

$$P_C(2k+1) = P_k^6(6,7) = \frac{\binom{6}{k}\binom{7}{6-k}}{\binom{13}{6}}$$

These probabilities and the cumulative probabilities of randomly drawing more or fewer than a given number of couples are shown in Table 14. Note that these probabilities are the same as those listed in Table 13 for the 7S, 6N case with C corresponding to 2(6-k)+1 and $\geq$ to $\leq$.

6.0 RESULTS

The numbers of above-median 1980-81 events associated with S trajectories for the variables shown in Table 12 are listed in Table 15, both for the combination of M events with S and of M

TABLE 13

Probabilities for assessing correlations between direction of air parcel origin and values of meteorological and chemical variables for the reduced set of 13 events, 1980-81

k	s = 11, n = 2 (a)			s = 7, n = 6 (b)		
	P_k^6	$P_{x\geq k}^6$	$P_{x\leq k}^6$	P_k^6	$P_{x\geq k}^6$	$P_{x\leq k}^6$
0	0	1	0	0.001	1	0.001
1	0	1	0	0.024	0.999	0.025
2	0	1	0	0.184	0.975	0.209
3	0	1	0	0.408	0.795	0.617
4	0.192	1	0.192	0.306	0.387	0.923
5	0.539	0.808	0.731	0.073	0.081	0.996
6	0.269	0.269	1	0.004	0.004	1

(a) M combined with S in Table 11

(b) M combined with N in Table 11

TABLE 14

Probabilities for assessing correlations between pairs of meteorological or chemical variables in the reduced set of 13 events, 1980-81

$C^{(d)}$	Probabilities		
	P_C (a)	$P_{x \geq C}$ (b)	$P_{x \leq C}$ (c)
1	0.004	1	0.004
3	0.073	0.996	0.081
5	0.408	0.923	0.387
7	0.306	0.617	0.795
9	0.184	0.209	0.975
11	0.024	0.025	0.999
13	0.001	0.001	1

(a) $P^{6}_{\frac{(C-1)}{2}}(6,7)$ (b) $\sum_{x \geq C} P_C$ (c) $\sum_{x \leq C} P_C$

(d) Number of pairs either both above or both below median.

events with S (Table 11). The numbers of couples between pairs of variables (Section 5.5 and Table 12) are shown in Table 16.

6.1 Correlations with Direction of Air Parcel Origin

Comparison of Table 15 with the probabilities in Table 13 shows that with M events lumped with S (giving 11 S and 2 N events) there are no correlations significant at the 95% level; indeed, for this distribution of S and N events no correlation at the 95% level is possible. The general trend is that high pack rise and S/N ratios are associated with N events and high concentrations and total amounts with S events.

When M events are lumped with N (giving 7S and 6N events) the snowpack rise is inversely correlated with S flow at the 99.9% confidence level (ie, high pack rise is associated with N flow), and high $[NO_3^-]$ is associated with S flow at the 99.5% level. The rest of the variables except for gauge depth, both concentrations and total deposition, have high values correlated with S flow at the 92% confidence level.

6.2 Correlations Between Meteorological and Chemical Variables

Comparison of Table 16 with the probabilities in Table 14 shows that the statistically significant correlations are the following:

1. Snowpack rise is inversely correlated with $[NO_3^-]$, $[H^+]$ and $[SO_4^=]+[NO_3^-]$.

2. Sample volume correlates directly with gauge depth and all total ionic amounts.

3. Gauge depth is also correlated directly with total NO_3^- and H^+.

4. $[NO_3^-]$ is directly correlated with $[H^+]$ and $[SO_4^=]+[NO_3^-]$.

5. The four total amounts (NO_3^-, $SO_4^=$, H^+, and $SO_4^=+NO_3^-$) form a mutually directly correlated set.

6. $[H^+]$ correlates directly with $[NO_3^-]$ and $[SO_4^=]+[NO_3^-]$, and inversely with snowpack rise and $[SO_4^=]/[NO_3^-]$.

7.0 DISCUSSION

The fact that snowpack depth rise and precipitation sample volume collected correlate in opposite ways with air parcel direction of origin (Table 15, pack rise correlates inversely, volume directly with southerly flow) indicates that these two indicators of precipitation amount actually measure very different quantities. Pack rise increases most in colder northerly events depositing dry, loose snow, whereas sample volume tends to be large in events with moist, warmer southerly flow.

TABLE 15

Numbers of events above-median in the meteorological and chemical variables which are associated with southerly air-parcel trajectories

Trajectory Combinations	Variable											
	R	V	D	$[NO_3^-]$	NO_3^-T	$[SO_4^=]$	$SO_4^=T$	$[H^+]$	H^+T	S+N	(S+N)T	S/N
M with S[a]	4	6	6	6	6	6	6	6	6	6	6	4
M with N[b]	1 (e)	5 (d)	4	6 (c)	5 (d)	5 (d)	5 (d)	5 (d)	5 (d)	5 (d)	5 (d)	3

(a) Mixed events (M) combined with southerly events (S); Table 11.

(b) Mixed events combined with northerly events (N).

(c) Direct correlation significant at the 95% level or more.

(d) Direct correlation significant at the 90% level.

(e) Inverse correlation significant at the 95% level.

TABLE 16

Numbers of events for which pairs of variable values are either both above or both below the median

Variable	R	V	D	$[NO_3^-]$	NO_3^-T	$[SO_4^=]$	$SO_4^=T$	$[H^+]$	H^+T	S+N	(S+N)T
R											
V	5										
D	7	11 (a)									
$[NO_3^-]$	1 (b)	7	5								
NO_3^-T	5	13 (a)	11 (a)	7							
$[SO_4^=]$	5	7	7	7	7						
$SO_4^=T$	5	11 (a)	9	7	11 (a)	9					
$[H^+]$	3 (c)	9	7	11 (a)	9	7	7				
H^+T	5	13 (a)	11 (a)	7	13 (a)	7	11 (a)	9			
S+N	3 (c)	7	5	11 (a)	7	9	9	11 (a)	7		
(S+N)T	5	11 (a)	9	7	11 (a)	9	13 (a)	7	11 (a)	9	
S/N	7	5	5	5	5	9	7	3 (a)	5	5	7

(a) Direct correlation significant at the 95% level or more.

(b) Inverse correlation significant at the 95% level or more.

(c) Inverse correlation significant at the 90% level.

Nitrate concentrations are apparently strongly correlated with southerly flow and hydrogen ion and sulfate concentrations less strongly but still significantly. The less strong correlation may be due to the smelter emitters of SO_2 north of Muskoka. Both ionic concentrations and total ionic deposition are directly correlated with southerly flow.

The fact that significant correlations appear only when mixed-flow events are combined with northerly-flow events is principally due to the resulting sizes of the N and S sets. The interpretive effect of lumping M events with N is that an inverse correlation with southerly flow (such as that of snowpack depth increase) should be interpreted as a confirmation of the rarity of high pack-rise events in truly southerly flow but not as confirmation that high pack-rise occurs only in truly northerly flow. Similarly, the direct correlation of pollutant content with southerly flow confirms that truly southerly flow tends to carry high pollutant content, but not that only truly northerly flow is clean.

The significant pairwise correlations in Table 16 can be summarized as three general effects:

1. High total ionic content is associated with high precipitation volume.

2. Nitrate concentrations (in equivalents) are in these events generally larger than sulfate concentrations, and the dominant contributor to precipitation acidity is HNO_3.

3. Events in which the snow depth increase is great tend to have relatively low precipitation ionic concentrations.

The first of these is not unexpected but does contradict the hypothesis that the total pollutant load deposited by storms is essentially constant, with larger storms having proportionately lower concentrations. The further correlation of high volume with southerly flow connects high total ionic deposition with southerly flow.

The second indicates that in these winter events nitrate acidity dominates sulfate acidity in the precipitation, which is reflected in $[SO_4^{=}]/[NO_3^{-}]$ ratios being less than unity. A similar dominance of nitrate over sulfate was observed in the snowcore samples and bulk deposition in 1980-81 (Table 5).

The third effect, through the inverse correlation of snowpack rise with southerly flow, is a result of the relative cleanness of northerly flow.

8.0 CONCLUSIONS

Because of the paucity of chemical data for 1978-79 no firm conclusions can be drawn as to the origin of the more severe effects of spring runoff upon fish eggs observed in 1979 relative to 1981.

The low pH observed in the single 1979 bulk deposition sample (Table 4) is probably not significant and is not reflected in a significantly lower pH value for the 1979 snowcore as compared to the 1980-81 values.

In the absence of any apparent chemical explanation for the more severe effect it appears reasonable that the timing of the melt (Section 3.0) may have been the major determiner of the severity of biological effects; however, without more complete chemical data it cannot be firmly concluded that differing ionic loads in snowfall were not responsible for the differing severities of the spring runoff.

The detailed analysis of the 1980-81 chemical and air parcel trajectory data led to three conclusions about the winter events studied:

1. Higher ionic concentrations are associated with precipitation carried in southerly flows.

2. Nitric acid is the dominant precipitation acidifier.

3. Events dropping large total amounts of precipitation tend to deposit large total ionic loads. High-volume events are usually southerly in air parcel origin.

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Approved:

D. Harrison
Manager
Chemical Research Department

Submitted:

for J.E. Grabenstetter
Research Chemist
Atmospheric Research Section

JEG/mf

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APPENDIX 1

AIR PARCEL TRAJECTORIES OF MAJOR SNOW EVENTS, 1978-79

—— 18Z NOV. 21 - 18Z NOV. 23

–·– 06Z NOV. 22 - 06Z NOV. 24

---- 12Z NOV. 22 - 12Z NOV. 24

FIGURE A1-1

1978-79 EVENT 1: 23-24 NOVEMBER 1978

925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-2
1978-79 EVENT 2: 30 NOVEMBER - 1 DECEMBER 1978
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-3
1978-79 EVENT 3: 10-11 DECEMBER 1978
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

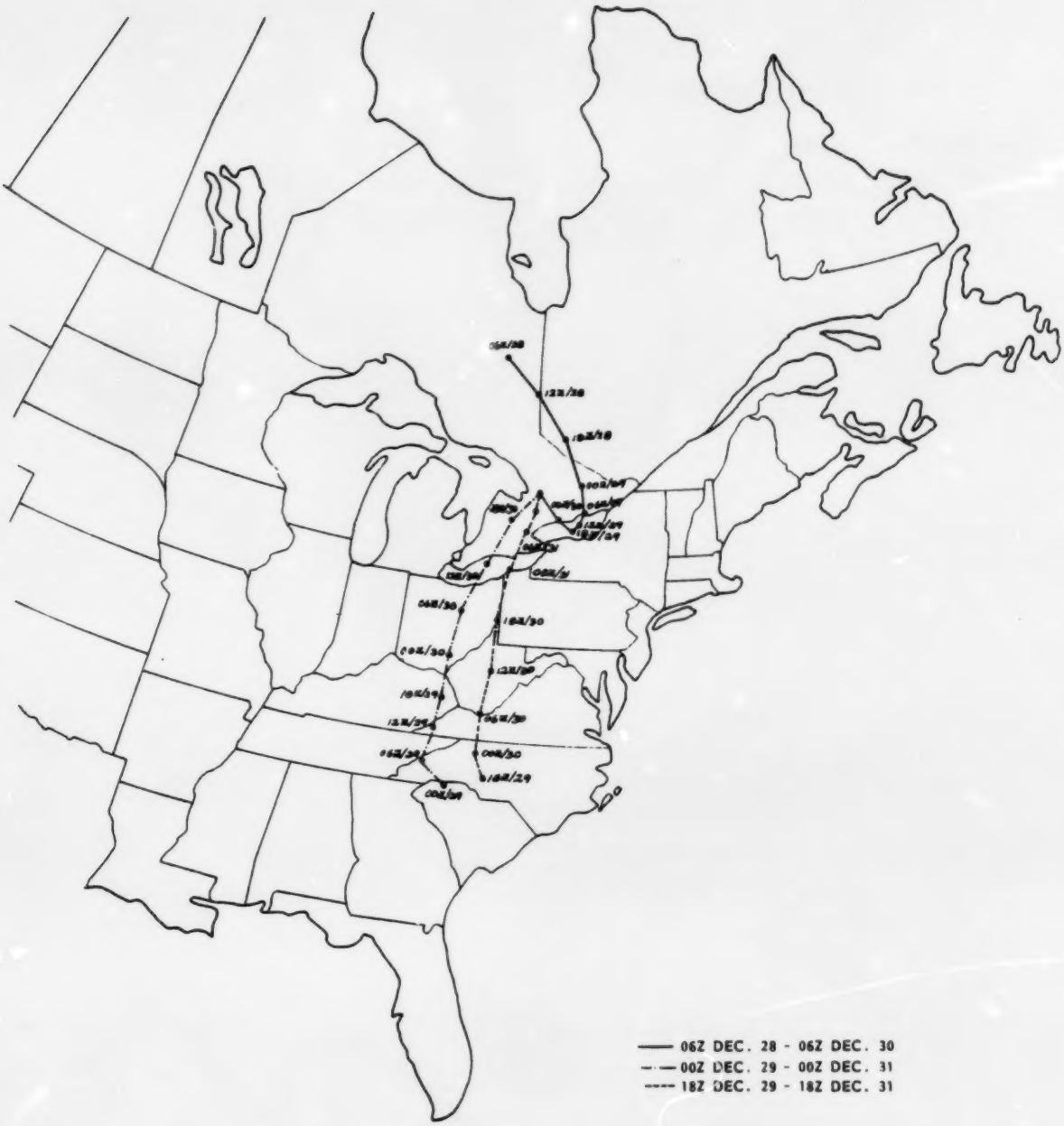

FIGURE A1-4
1978-79 EVENT 4: 30-31 DECEMBER 1978
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-5
1978-79 EVENT 5: 4-5 JANUARY 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-6
1978-79 EVENT 6: 9 JANUARY 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-7
1978-79 EVENT 7: 13-14 JANUARY 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

84-191

200258 RI

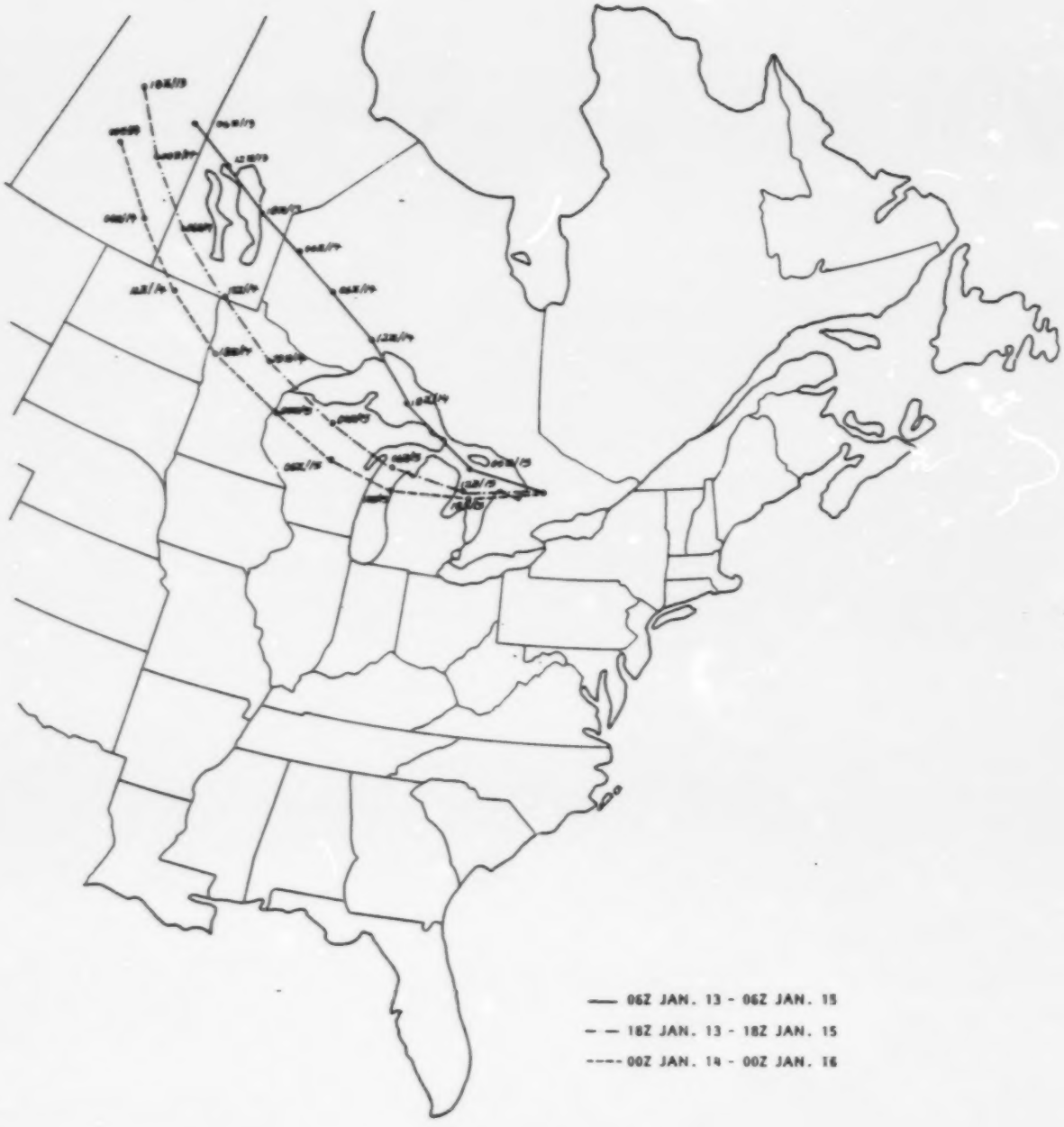

FIGURE A1-8
1978-79 EVENT 8: 15 JANUARY 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

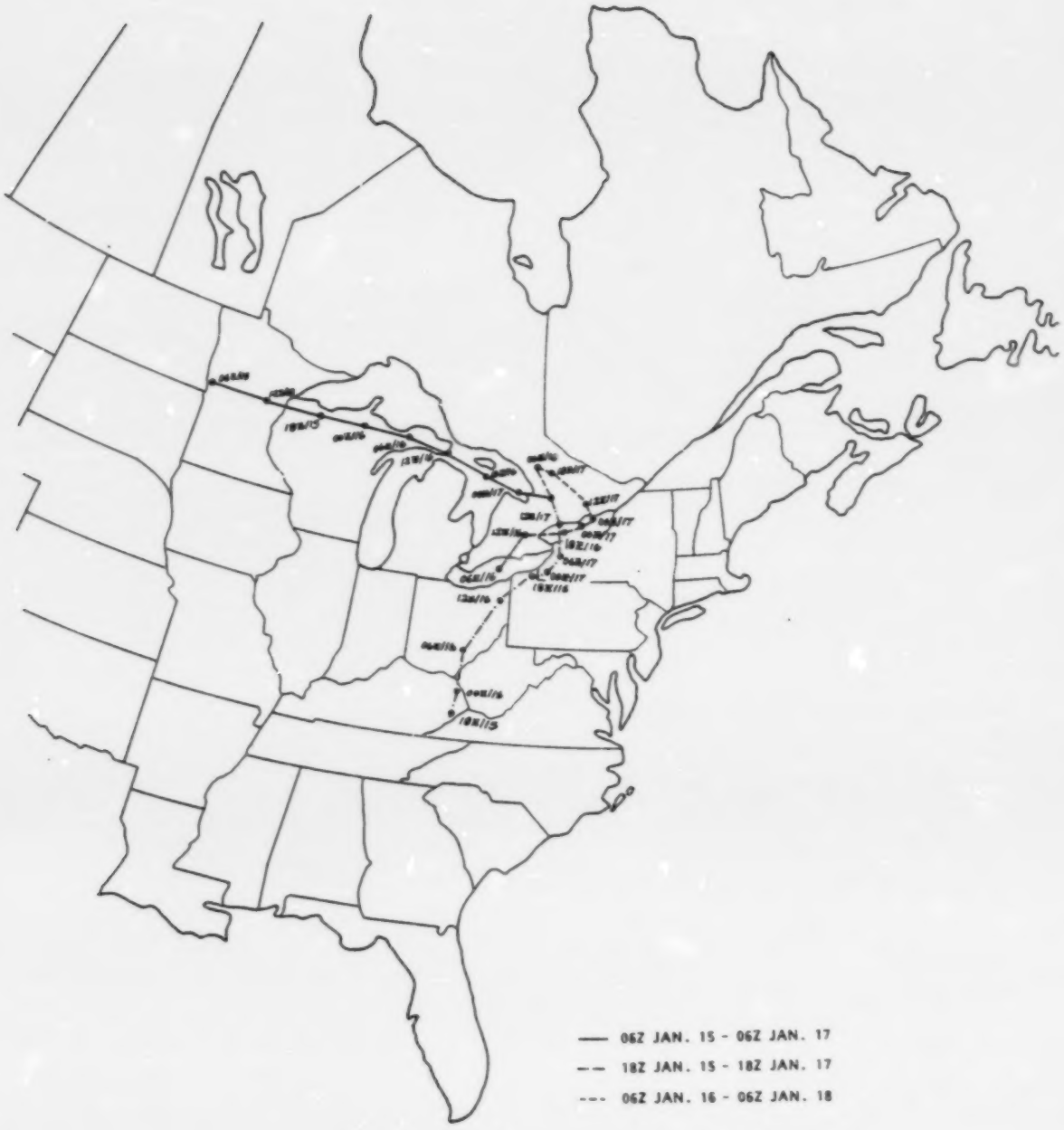

FIGURE A1-9
1978-79 EVENT 9: 17 JANUARY 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-10
1978-79 EVENT 10: 24-25 JANUARY 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-11
1978-79 EVENT 11: 4-5 FEBRUARY 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A1-12
1978-79 EVENT 12: 9-10 MARCH 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

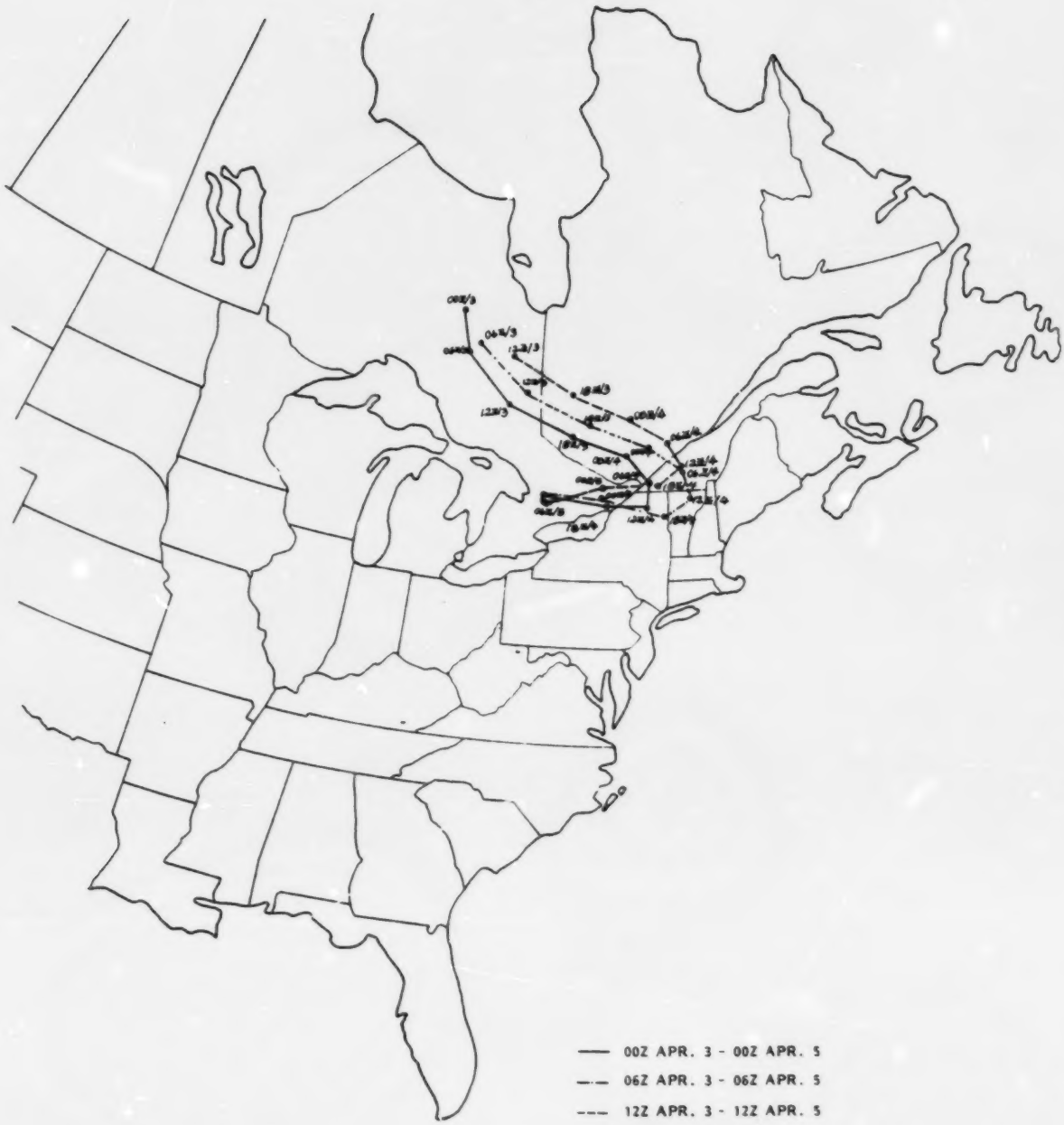

FIGURE A1-13
1978-79 EVENT 13: 4-5 APRIL 1979
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

APPENDIX 2

AIR PARCEL TRAJECTORIES OF MAJOR SNOW EVENTS, 1980-81

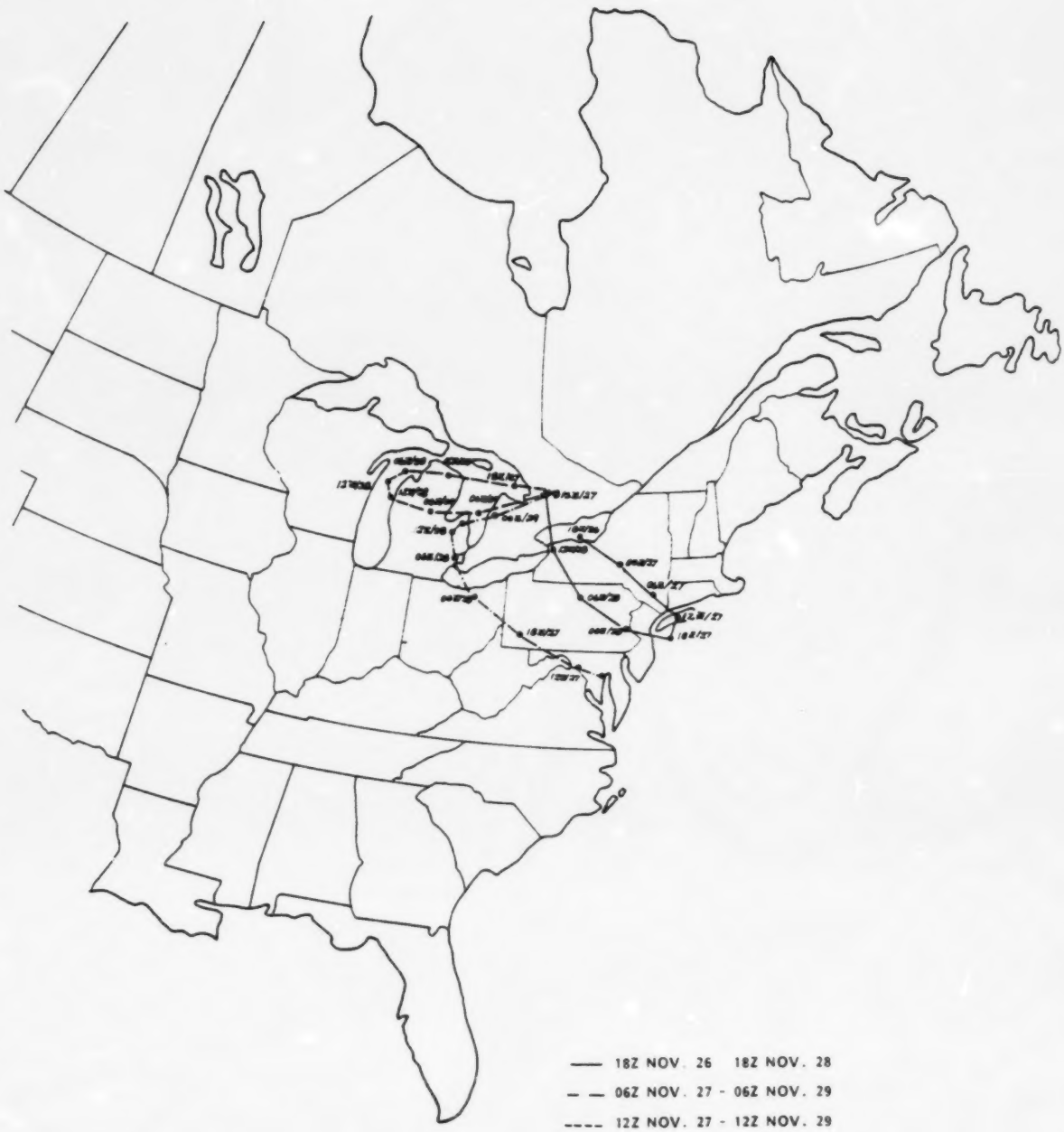

FIGURE A2-1
1980-81 EVENT 1: 28-29 NOVEMBER 1980
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

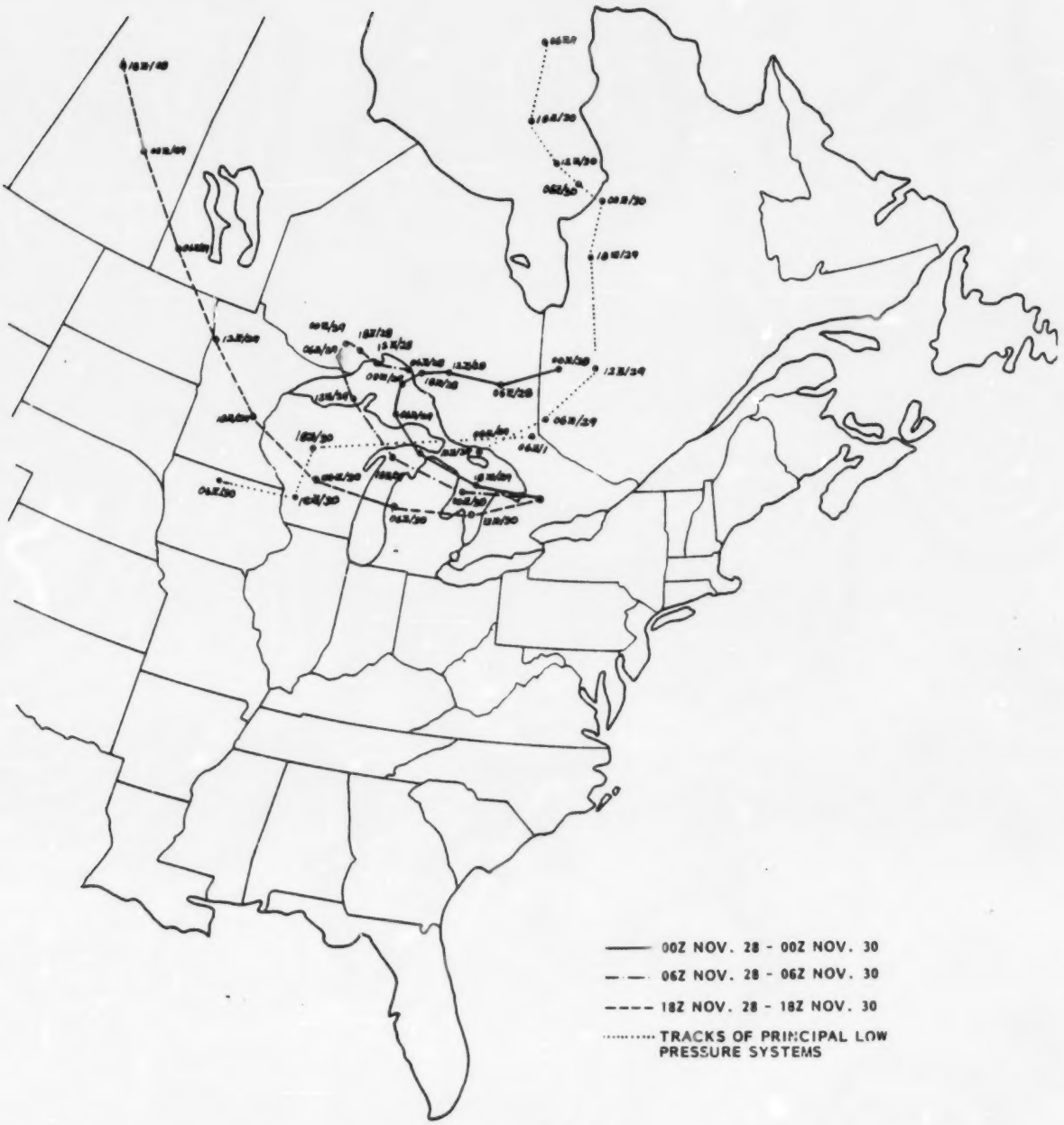

FIGURE A2-2

1980-81 EVENT 2: 29-30 NOVEMBER 1980

925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A2-3
1980-81 EVENT 3: 2-3 DECEMBER 1980
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

— 12Z DEC. 8 - 12Z DEC. 10

-·- 18Z DEC. 8 - 18Z DEC. 10

---00Z DEC. 9 - 00Z DEC. 11

FIGURE A2-4

1980-81 EVENT 4: 10 DECEMBER 1980

925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

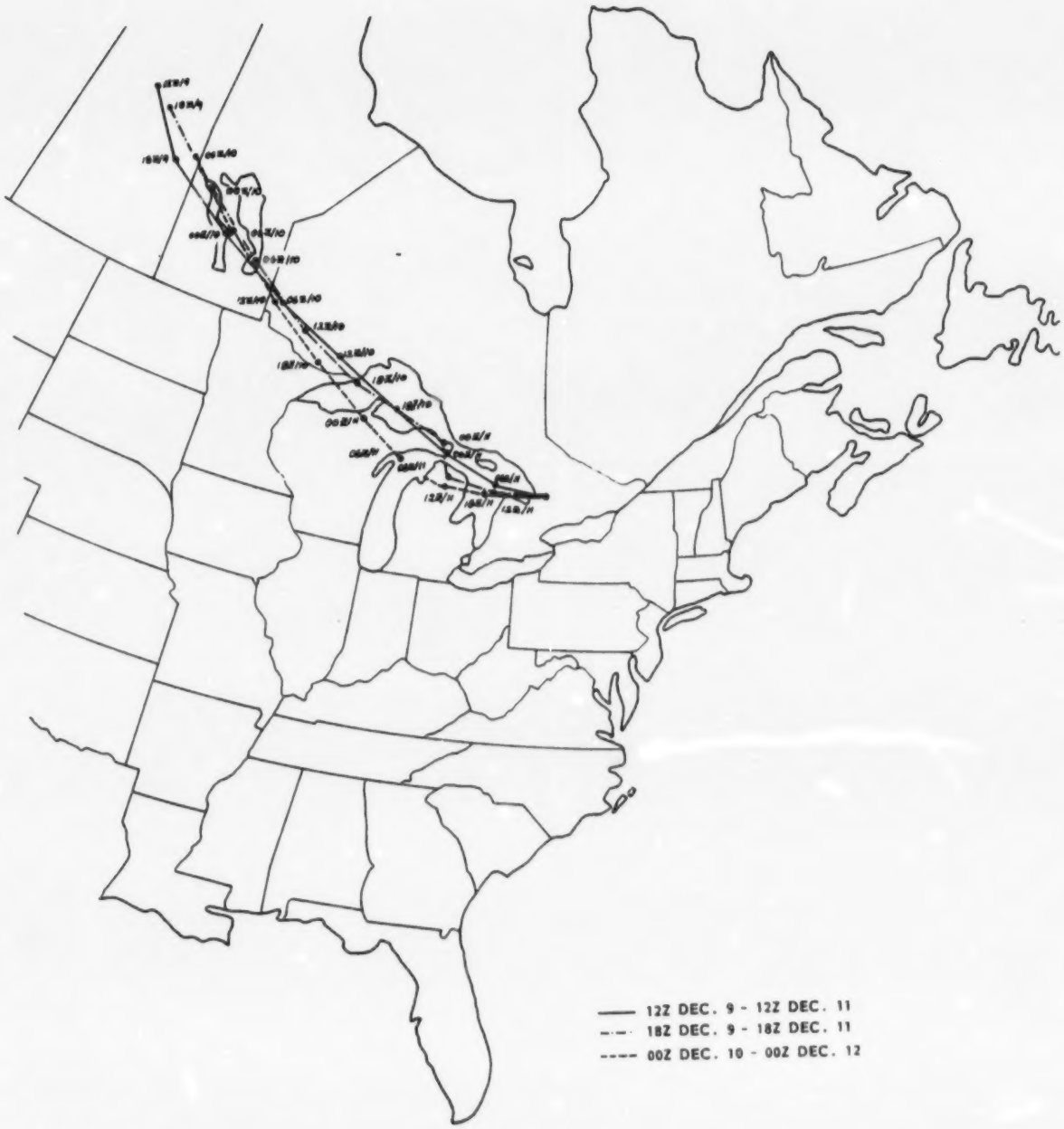

FIGURE A2-5
1980-81 EVENT 5: 11 DECEMBER 1980
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A2-6
1980-81 EVENT 6: 12-13 DECEMBER 1980
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A2-7

1980-81 EVENT 7: 13-14 DECEMBER 1980

925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A2-8
1980-81 EVENT 8: 17-18 DECEMBER 1980
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

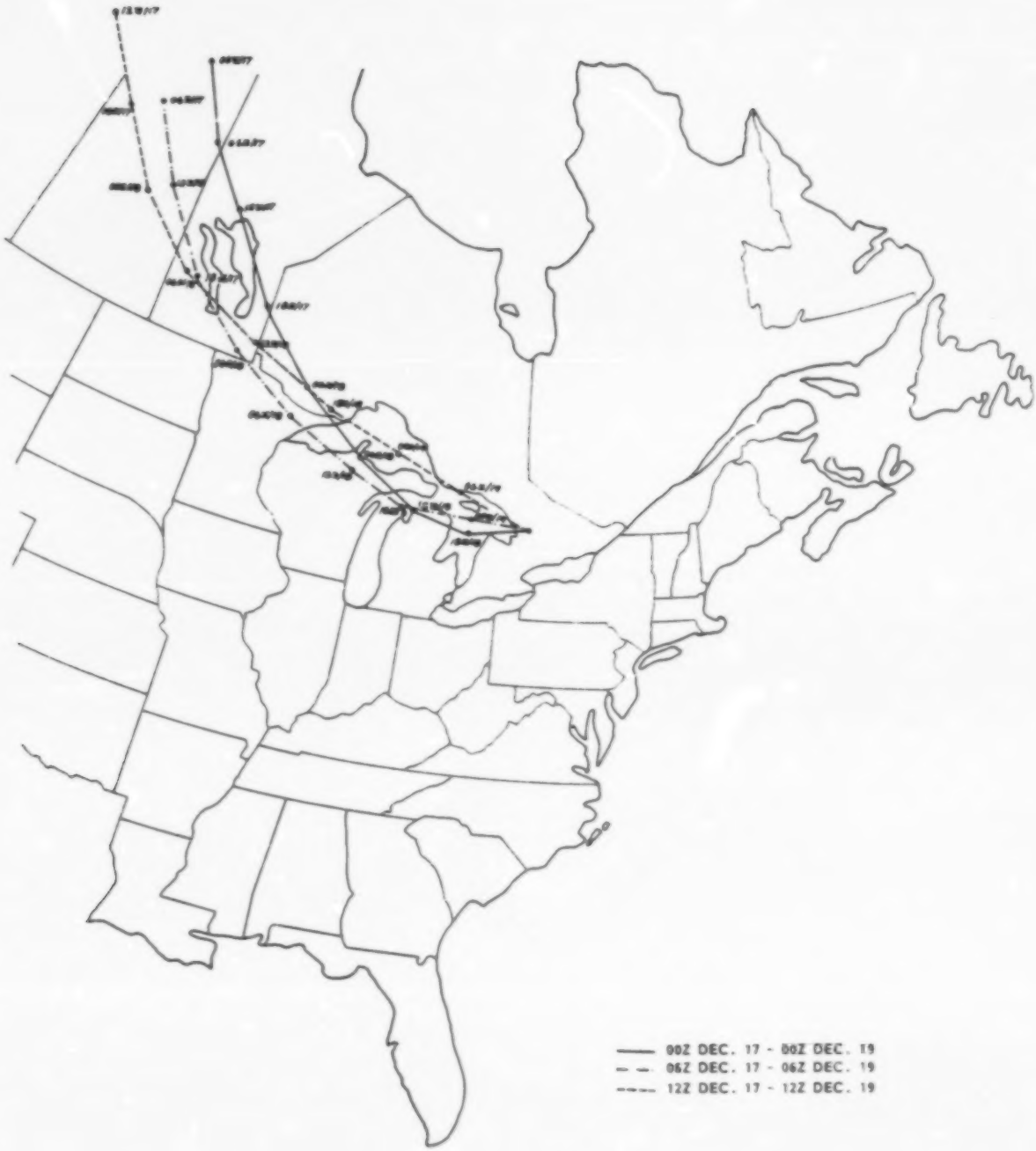

FIGURE A2-9
1980-81 EVENT 9: 18-19 DECEMBER 1980
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A2-10
1980-81 EVENT 10: 6-7 JANUARY 1981
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

84-191
200274 RD

FIGURE A2-11

1980-81 EVENT 11: 1-2 FEBRUARY 1981

925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A2-12
1980-81 EVENT 12: 6 FEBRUARY 1981
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

FIGURE A2-13
1980-81 EVENT 13: 28 FEBRUARY 1981
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

—— 06Z MAR. 2 - 06Z MAR. 4

–– 18Z MAR. 2 - 18Z MAR. 4

--- 00Z MAR. 3 - 00Z MAR. 5

FIGURE A2-14

1980-81 EVENT 14: 4 MARCH 1981

925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

— 18Z MAR. 13 - 18Z MAR. 15

-·- 00Z MAR. 14 - 00Z MAR. 16

--- 06Z MAR. 14 - 06Z MAR. 16

FIGURE A2-15
1980-81 EVENT 15: 15-16 MARCH 1981
925 mb BACKWARD TRAJECTORIES FROM MUSKOKA

200279 RD